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FINAL REPORT FOR WATERSHED HYDROLOGY PROTECTION AND FLOOD MITIGATION: PHASE I

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EXECUTIVE SUMMARY

To prevent natural resource degradation, the Vermont Department of Environmental Conservation is considering the development of acceptable practices for managing storm water runoff in urbanizing watersheds. Development of strategies to minimize or avoid future flood losses is also contemplated.

Stone Environmental Inc. (SEI) presents the results of a study to review and report on pertinent scientific literature which describes watershed land use, stream hydrology and morphology, aquatic ecosystems and surface water quality. SEI has reviewed flood damage survey reports to characterize damage due to the flood of August 5, 1995. SEI has prepared a recommendation for a technical analysis to determine, for Vermont conditions, thresholds of watershed land use change and watershed development/urbanization which, if exceeded, will result in unacceptable hydrologic reaction or aquatic ecosystem degradation.

Stream runoff and channel morphology reflect the magnitude and frequency of water and sediment inputs to the hydrologic system. Climate, vegetation, geology, and human influences are the dominant controls on water and sediment discharge. Alterations in these factors often initiate changes in the sediment-water relationship if the disruption is sufficiently large.

Geomorphic properties of a stream channel depend upon the hydrologic conditions controlled by the attributes of the watershed. Flooding is a natural phenomenon and has a specific probability of occurring in any given year which reflects the attributes of the watershed and the driving force of climate. Because flooding is a natural part of a stream's hydrologic regime, stream systems have been adjusted to the occurrence of overbank flows over geologic time.

Human-induced land use changes cause various hydrologic and geomorphic adjustments, including alterations in the size and timing of flood peaks and in the magnitude and type of soil erosion. Changes in land use and land cover affect the magnitude-frequency relationship of runoff by reducing the infiltration capacity of the soils in the watershed. These land use changes are subsequently expressed in significant changes in stream channel characteristics. Watershed scale changes such as urbanization, logging, and/or agriculture change the natural rainfall-runoff regime in such a way that large floods begin to occur more frequently and a stream's hydrologic regime becomes more "flashy" — peak discharges get larger, and baseflow becomes lower. These hydrologic changes generate significant geomorphic adjustments as stream channels tend to get deeper, steeper, and wider and transport a greater volume of sediment as accelerated soil erosion also tends to occur with the development of watersheds.

In general, the changes in stream hydrology and morphology are due to a disequilibrium in the channel caused by increases in sediment and water discharge. Land use changes such as urbanization, logging, changing agricultural practices, and channelization/dredging can cause these equilibrium upsets by increasing runoff. Urbanization creates impervious surfaces within a watershed. The infiltration capacity of the land surface decreases and water is able to run off more quickly, which alters the hydrologic regime.

Impervious surfaces and storm sewerage associated with urbanization enhance the peak discharges and therefore the mean annual floods. Channelization can restore low flows and reduce flooding upstream. However, downstream effects of channelization have been shown to include greater flooding, larger stream gradients and increased channel velocity.

High intensity, short duration storms, or micro-storms may have some geomorphic impact in watersheds. However, their impact will be enhanced by alterations in land use. Micro-storms can produce significant increases in erosion and sediment delivery to streams which in turn will cause geomorphic change, but these changes will be more drastic for developed than for undeveloped watersheds.

The literature shows that changes in land use were associated with significant changes in biological communities. However, the nature and magnitude of these changes varied considerably among studies. Direct effects may result from the introduction of hazardous material into the stream that directly kills fish and/or limits their reproduction. Other more indirect effects occur from watershed development and land use change that secondarily affect the ecological integrity of streams. Changes in the hydrologic regime by agricultural development, logging, and/or urbanization may cause significant geomorphic adjustments that alter and degrade fish habitats — thus limiting their reproducibility and survival.

A qualitative assessment of flood damage in seven Vermont towns was conducted in this study. The total number of damage incidents in each town was tabulated and compared to the total number of avoidable damage incidents. The result is a range of 29 to 58 percent of the total number of damage incidents that could have been avoided. The total dollar amount for all flood related damage to public property is tabulated along with the total dollar amount of what was determined to be avoidable damage. The avoidable dollar amount ranged from 28 to 61 percent of all money spent on flood repairs.

The literature review demonstrates that measurable impacts to the watershed from development and land use change will occur, but it is difficult to establish a specific minimum threshold for the magnitude of land use change that causes statistically significant hydrologic change -- and more importantly, the minimum specific hydrologic change that will cause statistically significant geomorphic and ecological change. In an effort to quantify these thresholds for Vermont environmental conditions, the Vermont Agency of Natural Resources has requested a scientific investigation (Phase II).

Phase II must be able to establish the current conditions of Vermont streams and also indicate what they should look like to function hydrologically and ecologically. Therefore, the approach taken for Phase II must establish the magnitude of hydrologic, geomorphic, and ecological conditions of both disturbed and undisturbed streams in Vermont.

Phase II should be a two-pronged approach: the first approach is a field component, and the second approach is based on already available data. For data collection, we suggest that a detailed habitat unit classification scheme be conducted along a selected range of stream reaches: this approach will reveal the geomorphic characteristics, the ecological characteristics, and the links between the two.

In order to establish the baseline conditions of Vermont streams and then to establish the magnitude of human induced impacts, we recommend that the habitat unit classification be conducted on numerous stream reaches of each of the following five conditions.

1. Undisturbed/"pristine" lands
2. Agriculturally-disturbed lands
3. Urban-disturbed lands
4. Lands that will soon be developed
5. Lands downstream of land soon to be developed.

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1.0 INTRODUCTION

The objective of this report is to present the results of Phase I of the Watershed Hydrology Protection and Flood Mitigation Project. Included in this report are:

1. a general description of watershed hydrology
2. the reviews and evaluations of the FEMA Damage Survey Reports
3. the literature reviews on land use change effects on stream hydrology and morphology and aquatic ecosystems
4. the recommendations for Phase II

Phase II will determine for Vermont conditions, thresholds of watershed land use change and watershed development/urbanization which, if exceeded, will result in unacceptable hydrologic reaction or aquatic ecosystem degradation. A glossary of terms used in this report may be found in Appendix 4.

2.0 DESCRIPTIONS OF WATERSHED HYDROLOGY, NATURAL STREAM DYNAMICS AND CAUSES OF CHANGE INHERENT TO STREAM SYSTEMS

Stream runoff and channel morphology reflect the magnitude and frequency of water and sediment inputs to the hydrologic system. Climate, vegetation, geology, and human influences are the dominant controls on water and sediment discharge. Alterations in these factors often initiate changes in the sediment-water relationship if the disruption is sufficiently large. Natural stream systems typically possess a relatively constant relationship of inputs (e.g. rainfall) and outputs (e.g. sediment transport) and demonstrate a systematic change in channel properties with increasing watershed area. A stream's watershed is a geographic and hydrologic unit that encompasses all the area that collects and drains runoff to the stream. Stream channel characteristics strongly reflect the size and character of the watershed it drains, and the dimensions and condition of the stream channel depend upon inputs occurring directly within the channel as well as on, and throughout, the watershed. The linkage of the tributaries with the main stream within a watershed have been developed and inter-connected over geologic time such that changes occurring within a tributary stream will be propagated downstream to the main stream, just as changes in the larger stream will be communicated to upstream locations within the watershed. These upstream-downstream linkages are related by topographic and elevation controls. The fluctuations in elevation of the main stem control the gradient and elevation of the tributaries, while the tributaries supply sediment and water to the main stem as the water moves down slope by gravity.

The size and dimensions of a stream at any point along a stream's length are controlled by the volume of runoff generated over that watershed upstream of that point. The most significant channel-forming flow is the bankfull flow which has an average frequency of occurrence of once in two-to-three years. Thus, channel properties are strongly linked to both the magnitude and the frequency of a particular runoff event; further indicating that the geomorphic properties of a stream channel depend upon the hydrologic conditions controlled by the attributes of the watershed. Because the channel size is linked to a flow with a frequency of once every two-to-three years, streams will overtop their banks at least once, on average, every two-to-three years. Flooding is a natural phenomenon and has a specific probability of occurring in any given year which reflects the attributes of the watershed and the driving force of climate. Because flooding is a natural part of a stream's hydrologic regime, stream systems have been adjusted to the occurrence of overbank flows over geologic time. Channel meandering and the development of floodplains depend upon flows overtopping their banks. For New England, there are numerous flood-producing mechanisms including rain, rain on snow, snowmelt, and hurricane induced floods. Snowmelt floods are the most common flood in Vermont, but the largest floods result from rain on snow or from high intensity precipitation events like hurricanes or micro-storms (high intensity, short duration storms). When a flood does occur, the impacts tend to be the enlargement of the channel in both size and width. Under natural conditions, the channel will recover to its pre-flood dimensions within a time frame of several years, and will return again to a channel size that can accommodate the two-year flood.

The equilibrium between inputs and outputs of natural systems does not necessarily indicate that a static relationship exists. Because of the highly variable nature of climate (daily, seasonally, and/or year-to-year), sediment transport and channel characteristics will also vary. Within undisturbed, natural systems, the hydrologic and geomorphic range in variation is quite small. Human-induced land-use changes cause various hydrologic and geomorphic adjustments, including alterations in the size and timing of flood peaks and in the magnitude and type of soil erosion. Changes in land use and land cover affect the magnitude-frequency relationship of runoff by reducing the infiltration capacity of the soils in the watershed. These land use changes are subsequently expressed in significant changes in stream channel characteristics. Watershed scale changes such as urbanization, logging, and/or agriculture change the natural rainfall-runoff regime in such a way that large floods begin to occur more frequently and a stream's hydrologic regime becomes more "flashy" -- peak discharges get larger, and baseflow becomes lower. These hydrologic changes generate significant geomorphic adjustments as stream channels tend to get deeper, steeper, and wider and transport a greater volume of sediment as accelerated soil erosion also tends to occur with the development of watersheds. The increased flooding and sedimentation occurring along a stream's length therefore reflect conditions upstream of that point as well as nearby conditions; thus efforts to mitigate the effects of human-induced disturbances must account for changes occurring on both a local and watershed scale.

Development and land use change greatly affect the sensitivity of streams and watersheds to both moderate and extreme floods. Although micro-storms have generated floods prior to settlement, development has increased the flood frequency associated with these climatic events. As a result of development, smaller magnitude precipitation events now generate similar levels of geomorphic impact that had been previously associated with more extreme precipitation events of the pre-settlement period. Besides altering the natural rainfall-runoff regime, development alters the seasonal timing of a micro-storm's impact. Summer floods were probably not very common during pre-settlement when trees blanketed the landscape and the natural system possessed a greater ability to absorb and infiltrate water. Because of agricultural plowing, road and house construction, and other forms of development, a micro-storm's occurrence in summer tends to produce more significant geomorphic effects due to the diminished infiltration capacity of the soils in the watershed. Thus the impacts of micro-storms are more frequent, more intense, and are more distributed throughout the year. The increased sensitivity of disturbed watersheds through land use change also appears in the ability of a stream to recover from a catastrophic flood. Disturbed channels in influenced watersheds tend to require longer time frames for recovery, and some remain de-stabilized for indefinite periods.

Another component of the watershed is the watershed's ecosystem. An ecosystem is the sum total of the organic (individuals, populations and communities of organisms and their byproducts) and inorganic components which influence energy flow and nutrient cycling within a given environment. In stream ecosystems, energy, in the form of carbon, enters via three main pathways. Algae - small, microscopic or almost-microscopic plants attached to hard surfaces on the stream bottom - are the major primary producers in streams, capturing energy from the sun via photosynthesis, and storing it as carbon. Carbon in dissolved form enters via runoff and groundwater discharge. Organic material, such as shed leaves falling from overhanging terrestrial vegetation, bring particulate carbon into the system. Primary consumers - in streams generally aquatic invertebrates living in association with the stream bottom, such as snails, crayfish, and aquatic insects - graze algae or consume organic detritus, using the energy for activity, growth, and reproduction. These primary consumers in turn provide energy for secondary consumers which prey upon them. In streams, secondary consumers are generally predaceous invertebrates and invertebrate-feeding fishes. Most perennial (permanently-flowing) streams contain these three trophic (feeding) levels. In some stream ecosystems a fourth trophic level is added by piscivores, organisms which consume fish (including predatory fish and humans, among others). Nutrients, are chemicals such as nitrogen, phosphorus, and sulfur required by organisms for growth and development. Nutrients enter the stream ecosystem in dissolved form from runoff, and contained in organic material. In contrast to energy, which flows through the ecosystem, nutrients, once they are incorporated into organisms, they can be recycled and made re-available via the activity of microorganisms, and organism excretion.

Streams and rivers comprise an immense range of environments, from tiny mountain springs to major river systems. However, two defining characteristics distinguish stream ecosystems from other aquatic and terrestrial ecosystems. These characteristics are largely derived from the dominant influence of a one-way flow of water — the one thing that makes a stream a stream.

First, streams are extremely open systems. Because of unidirectional flow, nutrients, materials, energy, and organisms are constantly arriving from upstream, and constantly being transported downstream. Therefore, conditions within a stream reach are "open" to the influence of processes and conditions upstream. In addition, because the water within the stream is derived from throughout the watershed, stream ecosystems are "open" to the influence of processes and conditions in the terrestrial ecosystem. The total area of a stream is tiny (on the order of acres) compared to the total area of the watershed which it drains (on the order of tens to hundreds of square miles). Therefore, critical aspects of stream ecosystems, such as water quantity, water chemistry, water temperature, and sediment input are dominated by land use characteristics within the watershed. While stream conditions are influenced by conditions throughout the watershed, the riparian zone

— the terrestrial environment immediately adjacent to the stream channel, and often subject to seasonal flooding, has a particularly important influence.

Second, the body form, behavior, physiology, and life cycle of most stream organisms is intimately associated with life in flowing water. For example, economically valuable stream fishes such as trout and salmon are adapted to stream environments in a number of critical aspects. Their streamlined body form allows them to swim against swift currents, which also deliver prey in the form of aquatic invertebrates swept up into the current. They require cold, rapidly-flowing water which has a high amount of dissolved oxygen. These species also require sufficient stream flow to keep fine sediments from smothering eggs and juveniles. Because variation in flow (the occurrence of floods and droughts) is a natural component of stream ecosystems, organisms tend to be adapted to this variation, and in some cases, require extreme flows to complete important parts of their life cycle. These include many species who rely on seasonally flooded streamside areas, known as riparian zones, to protect vulnerable juveniles from predators that reside in the main channel.

Because of the intimate relationship between stream organisms and the flow environments of streams, and the strong impact of watershed processes on flow, effects of land use on the timing, magnitude, and frequency of water flow-the hydrologic regime- may be a particularly important connection between land use and aquatic ecosystems. Hydrologic regime affects every important aspect of stream ecosystems. These include major changes in water quality, influencing both humans and natural populations. Changes in streamflow influence the delivery rate of materials and chemicals to streams, and influence their concentration once they are in the stream channel. Streamflow also has a major influence on stream temperature, due to the high heat capacity of water, the more water in the channel, the more slowly a stream will warm up or cool down. Stream temperature, along with organic material concentration, stream gradient and stream turbulence, largely determines the availability of oxygen for aquatic organisms, and the potential growth rates of harmful microbes. In addition to changes in water quality, changes in stream flow strongly determine habitat quality, the amount and suitability of living space for aquatic organisms. Streamflow determines the total amount of wetted area available to aquatic species. Further, effects of streamflow on the shape, or morphology, of stream channels, and the composition of the streambed, influence what types of organisms will be able to grow, survive, and reproduce within the stream channel. Understanding the specific relationship between land use, stream processes and ecosystem response are therefore key to maintaining stream ecosystem structure and function.

3.0 EVALUATION OF FEMA DAMAGE SURVEY REPORTS

As described in the previous section, floods are a natural phenomenon which occur even in an undisturbed watershed. The magnitude and frequency of flood events can be affected by land use changes such as urbanization, logging, agriculture, and channelization. The economic impact of floods is an important factor to be included in the discussions and decision making regarding land use change, stream dynamics, and water quality. Specifically, this section provides one approach to determining the economic impact of repairing or replacing roads, bridges, and/or retaining and conveyance structures which result from flooding.

3.1 Background

The Federal Emergency Management Agency (FEMA) provides both administrative and financial support to states in the event of serious flooding. On August 5, 1995 heavy rains resulted in flooding in many of Vermont towns with the Lamoille and Winooski River watersheds being especially hard hit. FEMA representatives prepared Damage Survey Reports (DSR) which identified and quantified the nature and extent of the flood damage. The DSRs are, therefore, a valuable source of existing information regarding causes of flood damage as well as the economic impacts of floods.

3.2 Methodology

For this report we reviewed the DSRs which targeted public improvements and not damage done to private property. Barry Cahoon of the Agency of Natural Resources had developed a list of criteria to evaluate whether the damage reported in the DSRs was avoidable. That is, whether inappropriate or inadequate changes to the drainage system contributed to the overall magnitude of the runoff event. These criteria were applied to four towns: Elmore, Underhill, Wolcott, and Worcester by Mr. Cahoon. The criteria include:

1) Deficient drainage structure (< Q25 capacity)
2) Otherwise inadequate infrastructure improvements/construction (roads, ditches, embankments, etc.)
3) Inadequately controlled and constructed curb cut access
4) History of periodic failure or flood loss
5) Failure of, or diversion by, other public or private structures (dam failure)

To expand upon the information from the four towns listed above, two additional towns, Hardwick and Middlesex, were evaluated using the same criteria. To gauge the objectivity and applicability of these criteria to all flood events in all towns the DSRs for these two towns were evaluated independently by both SEI and Barry Cahoon.

SEI reviewed the DSRs for Hardwick and Middlesex and then supplemented the information found in those reports with interviews with representatives from those towns. The DSRs for each town were prepared by different people and therefore some were more complete and clear than others. The DSRs for Middlesex were more comprehensive and only a phone interview was conducted to supplement the data. In the case of Hardwick, there was both a phone interview and a personal interview to clarify and expand upon the DSRs.

Representatives of Wolcott, Underhill, and Worcester were interviewed as well in an effort to obtain first hand accounts of the causes for the specific flood events in each town. While these representatives had been involved in compiling the data for the DSRs they did not have actual copies of the reports to refer to during the course of the interview thereby relying on memory. Therefore, each DSR was not specifically discussed and the interviews were more town-wide in context. Each town representative was asked the same series of questions which include:

1) Can you recall and comment on the flood of August 1995? (If yes continue interview, if no contact another town representative)
2) What would you consider to be the cause or causes of the flooding ?
3) Were the affected areas typically areas that experienced flooding in previous years?
4) Have there been any land use changes in the area? (Explain different types of land use change)
5) Would you say there was a relationship between the land use changes in the drainage area and the amount of flood damage?
6) What could be done differently to avoid flood problems in the future?

Information from the DSRs and the town interviews were combined to make a determination as to whether or not the damage could have been avoided. Where it was determined inadequate or inappropriate improvements were made then it was assumed that the damage could have been avoided. While this approach almost certainly overestimates the total *dollar value* of the land use impact it also provides a relative value with regard to the total *number of incidents* which could have been avoided.

3.3 Results

A summary of the DSRs for each of the six towns is included in Appendix 1. For the towns of Middlesex and Hardwick, independent reviews by ANR and SEI yielded similar results. The percentage of avoidable damage are reported two ways. First, the total number of damage incidents in a town was tabulated and compared to the total number of avoidable damage incidents. The result is a range of 29 through 58 percent of the total number of damage incidents could have been avoided. Second, the total dollar amount for all flood related damage to public property is tabulated along with the total dollar amount of what was determined to be avoidable damage. The avoidable dollar amount ranged from 28 to 61 percent of all money spent on flood repairs. The importance of this exercise is to generate an understanding of the economic effects of flooding resulting from inadequate or inappropriate land use changes.

Representatives of five towns in the flood ravaged area were interviewed to better understand the causes of flood damage and determine avoidable damage. A summary of the interviews is included in Appendix 1. Some town representatives did not believe that significant land use changes had occurred in the drainage area and therefore were not a significant contributing factor to the flood intensity. However, the Towns of Worcester and Hardwick both stated that recent logging operations upgradient of the damaged areas were directly responsible for the magnitude of the flood. Furthermore, the Town of Hardwick believes that the addition of homes and driveways on one road contributed to the flood damage. The Town of Underhill specifically identified road construction and impervious surfaces as a factor in the flood. Most of the towns believed that clearing debris or dredging would alleviate flood magnitude in the future. Two towns noted that ditch cleaning needs to become a regular part of road maintenance. Further many suggested that storm (precipitation) intensity has increased in recent years because the flooding has become more frequent and of greater magnitude.

Mitigation of inappropriate construction or inadequate drainage structures has been undertaken in many towns with a combination of local, state, and federal dollars. Two towns reported that the mitigation measures put in place following the 1995 flood withstood the heavy rains which occurred in the Summer of 1997.

4.0 LITERATURE SEARCH METHODOLOGIES

Identification of pertinent literature for review was conducted in an effort to maintain objectivity in the selection process. The initial search was done online by computer. Articles were then selected using specific criteria.

4.1 Hydrology and Geomorphology

One of the dominant objectives of this project was to identify the role of human disturbance on the hydrologic and geomorphic characteristics of Vermont streams. In order to ascertain the type and magnitude of the hydro-geomorphic changes, we have devoted most of our efforts to summarizing the diverse scientific literature concerning human impacts on watersheds and stream channels. The selection of articles was conducted by Dr. Frank Magilligan, Associate Professor of Geography at Dartmouth. To provide an unbiased sample of the literature reviewed, Dr. Magilligan conducted a computer search in CARL UNCOVER (An on-line service of the Colorado Alliance of Research Libraries) of published articles using the following key words: logging, clear-cutting, stream flow, sedimentation, urbanization, human impacts, land use, channelization, dredging, micro-storms, and flooding. The following selection criteria were used in selecting the articles by Dr. Magilligan:

1. Important concept
2. New England example
3. Similar soils/surficial geology
4. Similar physiography/bedrock geology
5. Similar climate
6. Similar impact such as influence from land use change or micro-storms

Included in the heading of each summary is an explanation sentence stating why information in the chosen article is relevant to this project. For example, an article which documented a study of pre- and post-colonial sediment source and storage in a watershed was relevant because it revealed how land use change can affect erosion and sediment yields. The relevance of an article was sometimes obvious from the article's title, but in some cases, it was not. Therefore, it was deemed necessary to include a statement as to why each particle article was important to include in the literature review.

Our literature search has addressed five major themes: agriculture, logging, urbanization, channelization/dredging, and micro-storms. These themes were chosen since all chosen articles appeared to fit into types of land use change categories. Literature consulted for this report regarding hydrology and geomorphology is listed in Section 8.0. Included in this list are applicable references which were expanded into 1-2 page summaries and labeled with the appropriate theme category. In order to remain objective in the literature review process, the hydro-geomorphic articles were read and summarized by SEI staff. These summaries are organized alphabetically and compiled in Appendix 2.

4.2 Aquatic Ecosystems

We identified four texts as general sources for understanding the ecological context of land use effects. These texts were chosen to fulfill the following two criteria: 1) provide a concise and effective description of aquatic ecology 2) provide effective reviews of the mechanisms and state of knowledge concerning the effects of land use on stream ecology.

In order to provide an unbiased sample of the state of current research on the effects of land use on stream ecology, we conducted a computer search using the Web of Science browser and database, covering the years 1990-1997 (present). We used the following key words in the search: land use, ecology, streams, rivers, fish, flooding, logging, and dredging. Of the references obtained we retained all that fulfilled the following criteria: 1) the work represents a case study involving original research (not a review) 2) the work concerns one of the categories of response listed in the matrix in Table 1, and 3) the work took place in a mesic, temperate-boreal environment, to promote relevance to Vermont conditions.

Literature consulted (see Section 9.0) includes reviews of these issues, specific case studies, and theoretical/conceptual work which relates environmental disturbance to ecosystems and biological communities. References which came up in the computer search were expanded into 1 page summaries (Appendix 3).

5.0 LITERATURE REVIEW

Articles were reviewed and a comprehensive summary of those articles was constructed**.** The literature review was conducted in two parts, topics on hydrology and geomorphology and topics on aquatic ecosystems.

5.1 Hydrology and Geomorphology

Literature on topics including hydrology and geomorphology and their relation to potential anthropogenic influences were reviewed. The review took a holistic approach where the role of anthropogenic impacts on both the local (i.e. stream channel) and watershed scale (i.e. changes in rainfall-runoff process) was evaluated. The effects of these impacts may sometimes be similar, and other times, they may be process-specific. The scientific literature was used to document specific hydro-geomorphic adjustments:

1. Changes in channel characteristics (increased channel cross-sectional area, changes in hydraulic geometry and width/depth ratios).
2. Changes in channel gradient and sinuosity
3. Changes in hydrologic regime (increased flood peak, decreased baseflow, changes in flow magnitudes and frequencies).
4. Changes in sediment transport (increased stream competence and capacity).

5.1.1 Summary of Findings

Geomorphic and hydrologic adjustments and the magnitude of the increase or decrease caused by land use change impacts are summarized in the Impact Matrix Table (Table 1). This table was generated by SEI from information found in empirical studies reviewed. If there was an increase in a specific hydrologic or geomorphic parameter for a particular impact (e.g. urbanization), the symbol + was entered into the table. If there was a decrease, the symbol - was used. The magnitude of that change was indicated by a number system where 0 = no impact, 1 = minor impact (<15% change), 2 = moderate impact (15-50% change), and 3 = significant impact (>50% change). If the change was statistically reported as a significant change, it was given a magnitude of 3. If no number was indicated, a magnitude of change or significance level was not reported in the literature for that parameter. When conflicting results were found among articles, i.e., one author observed an impact while another did not, both were reported in the table. For the channelization impacts (dredging and straightening) where two effects are listed, the first and second effects refer to the upstream and downstream (from the area of disturbance) effects, respectively. When information was not available because the impact on a parameter was not measured, n/a was entered to indicate “not available”.

In general the changes in steam hydrology and morphology are due to a disequilibrium in the channel caused by increases in sediment and water discharge. Land use changes such as urbanization, logging, agricultural practice alterations, and channelization/dredging can cause these equilibrium upsets by increasing runoff.

Urbanization creates impervious surfaces within a watershed thereby decreasing the infiltration capacity of the land surface and water is able to run off more quickly altering the hydrologic regime. One parameter directly affected by urbanization is lag time which is the time interval between the precipitation and the resultant discharge over time (Leopold, 1971; Graf, 1977; Carter, 1961; Anderson, 1970). Figure 1 displays the relationship between lag time and surface runoff. As the unit hydrograph A of a "natural" watershed in this figure shows, as time increases after a storm event, discharge increases and the area of the peak represents the volume of the surface runoff. However, as the unit hydrograph in B shows, with impervious surfaces there is a quicker surface runoff, lag time is reduced, and peak discharge is earlier and greater which therefore makes the runoff volume greater.

Impervious surfaces and storm sewerage associated with urbanization enhance the peak discharges and therefore the mean annual floods. Leopold, 1971, explained that the ratio of the peak discharge (mean annual flood) after urbanization to the peak discharge prior to urbanization increases as both percentages of impervious area and storm sewerage increase. The graph in Figure 2 shows that the mean annual flood for a one square mile drainage basin can be increased by a factor of 2.5 as impervious area increases from 0 to 100 percent. This figure shows that 60 percent impervious area and 60 percent sewerage results in the peak discharge to be from 3 to 4 times the mean annual flood. Furthermore, when there is 100 percent sewerage and 100 percent impervious area, the before/after urbanization peak discharge ratio increases to approximately 8. This graph therefore expresses the probability of increased peak discharges and hence flooding to occur with greater storm sewerage and impervious surfaces associated with urbanization.

Literature has shown that as land surface runoff increases from land use changes such as urbanization, logging, or agriculture, the peak rate of runoff increases (Jones et al., 1996; Cheng, 1989; Wright et al., 1990; Arnold et al., 1982; Wolman, 1967; Leopold, 1971; Fox, 1974; May et al., 1997; Crippen, 1965; Anderson, 1970; Thomas, 1990). Knox, 1977, has summarized the effects of runoff from various land uses for moderate, frequent rainfalls (Table 2). Table 2 shows that higher runoff values occurred in agricultural land compared to forest or native pasture land. The conversion of natural vegetation to agricultural land use can therefore result in elevated levels of surface runoff. Literature has also shown that with increases in impervious areas or with clear-cutting, the magnitude of a flood volume can increase (May et al., 1997; Anderson, 1970; Jones et al., 1996; Keppeler et al., 1990; Wright et al., 1990). Models have shown that increases in flood magnitudes are often more drastic for smaller more frequent floods as opposed to larger more infrequent floods (Krug et al., 1986). Along with the increase in flood magnitudes are increases in flood frequency. For instance, a channel which normally receives flows which exceed its banks every 1.5 to 2 years will receive those flows more often after urbanization. Literature has shown that increases in flood frequency occur from urbanization or logging (Carter, 1961; Arnold et al., 1982; Krug et al., 1986). Flood frequency may be reduced by stream channelization (Shankman et al., 1991), but other detrimental impacts may occur as a result of channelization which will be discussed later. In addition to changes in peak discharges, base flows can be reduced by land use changes. Knox, 1977, showed that base flows decreased as a result of increased surface runoff and decreased infiltration as land was cleared for agriculture use.

With increases in runoff during storms caused by land use changes such as logging and urbanization, there is an increased potential of longer floods. Major increases in high flow duration larger than a two year storm event have been observed in models simulating great increases (29%) in impervious areas (Booth, 1990). Hornbeck et al., 1970, also observed flood duration increases as a result of logging. When increases such as flood duration, magnitude, and frequency occur in a watershed, the surrounding floodplain areas are impacted longer, more often, and with more intensity potentially causing more environmental and economical problems.

In addition to urbanization, many hydrologic changes have been observed in clear-cutting as well as with road construction associated with logging. The level of impact from logging of course depends on the degree of logging (selective cutting, clear cutting, and road construction). Often comparisons have been made between logged and unlogged watersheds where, in general, basins with more clear-cutting showed significantly higher flows (Jones et al., 1996; Hornbeck et al., 1970; Keppeler et al., 1990). Clear-cutting practices therefore results in greater increases in peak discharges than partial cutting, i.e. the magnitude of hydrologic change can be a factor of percent area cut within a basin. Even when cutting is done selectively (not all at once), streamflow is still impacted. Keppeler et al., 1990, observed that streamflow augmentation occurred as a result of selective cutting over a three year period. Streamflow changes irregularly decreased following the first year after cutting. Rate of cutting (percent/year) is also a factor and can vary among logging operations affecting hydrology differently. Jones et al., 1996, found that more rapid cutting rates along with areas which experience cumulative cuts increase peak discharges.

Forest removal techniques can vary among logging operations. Cheng, 1989, reviewed data from various studies and compared the magnitude increase of annual peak flows for each forest removal technique used in these studies. Greatest increases were shown for 50% burned and clear-cut with 59% and 50% magnitude increase, respectively. Clear-cut of 21%, 30%, and 40% strip-cutting had magnitude increases of 24% (May flow), 21%, and 23%, respectively. For more detail on the authors, dates, and locations of these studies see Cheng, 1989.

Often changes in the hydrologic regime are restored after the forest has had some time to regenerate or recover, but the flows are usually still higher than pre-treatment levels (Jones et al., 1996). However, Thomas, 1990, observed that daily flows did not recover until 11 years after logging. The literature has shown that upsetting flow regimes caused increases in sediment loads (80% with road construction and 275% with logging) (Keppeler et al., 1990). Significant increases in sediment yields are often observed during the first years of logging with recoveries occurring later on (Thomas, 1990). Even though there is regeneration in forests and recovery after logging, there is still significant impact of increased water and sediment discharge for a long period of time.

Logging was not always found to increase all aspects of the hydrologic regime. For instance, Thomas, 1990, found no significant relationship between peak flows and a logged watershed probably because there were too few storms to evaluate. However, he did observe moderate (19%) increases in total storm discharge with no changes in quick flow (defined as the discharge which enters the stream immediately following rainfall) indicating a possible increase in base flow.

Some of these hydrological impacts occurred primarily due to road construction associated with logging (Jones et al., 1996; Keppeler et al., 1990). Wright et al., 1990, found that land use in roads only, in close proximity to the streams, did not significantly impact the flow regime because they intercepted water late in the flow regime. However, Jones et al., 1996, observed that road construction (comprising 6% of a watershed) alone caused a significant number of storms to have increased peak discharges in small basins while clear-cutting alone showed significant increases in storm flow volumes. There was no statistically significant increase in average peak discharge from roads alone due to the high variability of the storm events evaluated. When road construction was combined with patch clear-cutting ranging from 10-25% of basin area, significant long-term increases in peak discharges were observed for both small and large basins. Roads enable the increase of peak discharges because they can convert the subsurface flow paths to surface flow paths (Jones et al., 1996).

Within the urbanization/suburbanization scenario, hydrologic parameters can be impacted as a result of the addition of roads. Graf, 1977, found that the addition of a road network to a surburbanizing area caused the drainage density of a watershed to increase by 50% and that this increase led to a more rapid collection of runoff and reduction of overland flow which was observed in the reduction of lag time and increase in the storm hydrograph. Therefore, the creation of paved roads which increases impervious surfaces within a watershed can also result in hydrologic changes and the degree of these changes will depend on how much the drainage density of the basin has been altered. It is often difficult to isolate effects of town roads from other types of development since road construction often accompanies sewering and the creation of impervious surfaces from buildings and parking lots. However, Hammer, 1972, observed that channel enlargement effects were greater from sewered streets and area of major impervious parcels than from unsewered streets and impervious area involving detached houses.

One way to determine hydrological effects from roads is to observe how much of the total impervious surface in a watershed is attributed to the road network. Anderson, 1970, demonstrated that as a coefficient for imperviousness (determined by the percentage of a watershed covered by impervious surfaces) increases, hydrologic factors such as lag time and flood magnitude and frequency increase. If the percentage of the impervious surfaces in the basin is rather small, the coefficient of imperviousness is 1.00 and lag time was not reduced as significantly compared to coefficients of 1.3. The impact of town roads can therefore be assessed based on the degree of imperviousness or drainage density alteration caused by the addition of the roads. Roads associated with logging would have the same effects as roads associated with urbanization during the construction phase. However, logging roads are usually not paved while urban roads are thereby increasing their imperviousness and greater runoff potential.

Alterations in the hydrologic regime can cause major effects on stream morphology. Figure 3 displays the sequence of events for hydro-geomorphic change which can occur when surface runoff is increased. In general, the sequence of events begins with increases in surface runoff. Peak flow and sediment discharge increases and base flow reductions lead to hydro-geomorphic changes which eventually result in riparian degradation and diminished ecological integrity. For instance, as runoff is increased, the potential for erosion within the channel, especially along the banks, is increased (Wolman, 1967; Fox, 1974; Costa, 1975; Knox, 1977). One major effect observed in the literature is the increase in channel width as a result of erosion (Arnold et al., 1982; Wolman, 1967; Leopold, 1971; Fox, 1974; Gregory et al., 1992; Simon, 1994; Krug et al., 1986; Hammer, 1972; Knox, 1977; Emerson, 1971; Booth, 1990). Alterations in channel morphology, such as increased channel width and depth, result in a greater carrying capacity of water and sediment (Leopold, 1971; Emerson, 1971; Ebisemiju, 1989). Often channels are widened by larger peak flows and flood frequencies which enhance bank erosion and scour (Arnold et al., 1982; Wolman, 1967; Leopold, 1971; Fox, 1974). When channels are widened as a result of bank erosion and scour, the cross-sectional area of the channel is increased.

Cross-sectional areas are also increased as a result of incision of channels caused by elevated shear stress on the bed. The degree of channel incision which can occur depends on the slope of the stream. Studies have been documented which show increases in channel incision as a result of land use change or channelization (Orbock-Miller, 1993; Booth, 1990; Wyzga, 1996). Booth, 1990, also showed through modeling that urbanization can cause cross-sectional area increases as high as 75%. Moderate increases (18%) in cross-sectional area have been observed by urbanization (Krug et al., 1986). Conversion to agricultural land has also shown to cause channel enlargement (Knox, 1987). Different land uses will affect channel enlargement differently. For instance, open land will have a channel enlargement ratio approximately 8 times less than areas with contiguous impervious surfaces (Hammer, 1972). When channels are enlarged, their width to depth ratio is thereby increased. Changes in this parameter often gives a measurement of geomorphic change over time. Knox, 1977, observed considerable increases in the width to depth ratio in a channel impacted by increased agricultural land use. Orbock-Miller, 1993, also observed higher width-depth ratios as a result of clear-cutting and subsequent channel incision caused by more frequent storms. Direct anthropogenic influences which can cause increases in erosion, channel width, the width to depth ratio, and cross-sectional area are channelization or dredging (Emerson, 1971; Mossa et al., 1997;).

As mentioned earlier, sediment loads often rise as a result of land use changes. When the surface runoff increases, more sediment is discharged which can lead to higher levels of suspended sediment and variable changes in stream morphology. There have been numerous studies documenting significantly higher levels of sediment loads with increased sediment discharge from urbanization, logging practices, or channelization/dredging (Arnold et al., 1982; Fox, 1974; Wolman, 1967; Wolman et al., 1967; Simon, 1989; Wilcock et al., 1991; Phillips, 1993; Ebisemiju, 1989). As sediment discharge becomes greater, there is also a possibility of more bedload material downstream. Increased bedload material has been observed as a result of changes to agricultural and urban land uses as well as channelization (Knox, 1977; Fox, 1974; Arnold et al., 1982). With concurrent increases in bankfull discharges, elevated levels of overbank sedimentation are often observed. Several studies have shown greater overbank sedimentation as a result of land use changes (Orbock-Miller, 1993; Knox, 1977; Knox, 1987; Arnold et al., 1982; Phillips, 1993). Overbank deposition increases as a result of land use change because the amount of sediment which runoffs from the uplands is no longer balanced with the amount of sediment which is in transport, i.e., upland erosion rates are greater than the transport rates. Knox, 1987, also observed that overbank deposits were coarser in some areas representing responses to greater flood frequencies and magnitudes. Floods of greater magnitudes have the capacity to entrain and deposit larger particles due to elevated energy capabilities of the stream.

The most extreme instances of geomorphic changes such as bank erosion, coarse grain sediment aggradation, and increased sediment yields are observed during the construction phases of urbanization (Wolman, 1967). Following construction, flows still remain high causing accelerated bank erosion and increased bedload deposition downstream from the disturbed area (Arnold et al., 1982).

Another major morphological impact of the stream channel system is reduction of riparian buffer area (May et al., 1997). Riparian areas and geomorphic processes such as overbank sedimentation play an important role in providing storage regions for nutrients (DeAndrea, 1994; Lowrance et al., 1985). Therefore, reducing these areas may increase nutrient runoff within the watershed. Other impacts which have shown increases in nutrients have been clear-cutting especially in areas which were not revegetated after clear-cutting (Sopper, 1975).

As land use change from pasture/idle to agricultural land can affect the hydro-geomorphic regime, these effects can sometimes be mitigated. Land use converted back from agricultural land to pasture/idle land is capable of reducing flow rates and therefore erosion and sediment loads in streams (Kuhnle et al., 1996). The conversion of the land use results in less runoff leaving the uplands and hence a reduction in upland sediment production.

Conservation practices are able to mitigate problems with runoff and soil erosion. Potter, 1991, observed that agricultural land use practices such as conservation tillage was responsible for decreasing flood volumes and increasing base flows. Improvement of existing land use practices such as strip cropping and crop rotation have been shown to reduce geomorphic problems such as high rates of overbank sedimentation due to reductions in sediment loads (Knox, 1987; Costa, 1975; Magilligan, 1985). Other results of improvements of land use practices include decreases in bankfull channel capacities, bankfull widths, bankfull discharges, peak discharges, and flood frequency (Magilligan, 1985). Implementing soil conservation practices therefore in agricultural areas aids in the restoration of hydrologic regimes.

Channelization or straightening of channels, which is sometimes used to mitigate problems with streamflow dynamics, is also capable of impacting the natural hydro-geomorphic condition of streams. In addition to the hydro-geomorphic parameters already discussed which may be impacted as a result of channelization, streamflow velocity, grain sizes in transport, and pool and riffle sequences are also affected. Channelization and dredging have shown to increase streamflow velocities, but have also shown to elevate base or low flows (Shankman et al., 1991; Wilcock et al., 1991). Increases in low flows are usually much greater than increases in higher streamflows (Wilcock et al., 1991). Even though channelization can restore low flows and reduce flooding upstream, downstream effects of channelization have been shown to include greater flooding, larger stream gradients, and increased channel velocity (Shankman, 1996; Emerson, 1971; Waters, 1995; Nakamura, 1997). In channelized streams, rises in stream velocities will often cause further channel incision and enlargement (Shankman, 1996; Simon, 1994). Nakamura et al., 1997, found that degradation upstream of channelization occurred due to greater flow velocities and average slope increases from 0.1% to 0.2%. Downstream from channelized areas, increased bed aggradation was observed as well. Simon, 1994, observed a sequence of geomorphic events from channelization which involved 1) degradation upstream from the point of disturbance 2) sediment load increases 3) aggradation as a result of bed recovery and 4) channel width adjustment and bank-slope development as a result of bed changes. In addition to hydro-geomorphic impacts from channelization, channel complexity is also affected (Shankman, 1996). Sediment load increases generated by channelization can enter wetland areas in excessive amounts changing the soil structure and altering the type of vegetation which is grown (Nakamura et al., 1997). Therefore, channelization may provide some control in one reach of a stream, but downstream hydro-geomorphic as well as habitat diversity impacts are inevitable.

Another type of channelization often thought of in mitigating flood problems is dredging of stream beds to provide more area for the water discharge to flow through. When streams are dredged, however, there can be a direct influence on the sediment and flow characteristics within the channel. Collins et al., 1989, observed a general downstream reduction in grain sizes of bed material which was due to a decline in gradient caused by the dredging. The main problem with harvesting gravel according to Collins et al., 1989, is that the extraction rate of coarse sediments does not equal the natural replenishment. Impairments such as this along with eliminations in natural pools and riffles from dredging may alter the aquatic habitat quality of the stream (Wilcock et al., 1991).

One may think that these potential hydro-geomorphic changes may not be limited to land use disturbances. In many studies, precipitation patterns were looked at to correlate climatic change with geomorphic change. However, Potter, 1991, did not find any significant correlation between trends in climatic variability and hydrologic changes which he concluded to signify that the trends were caused by agricultural land use changes. Arnold et al., 1982, also could not find correlations of precipitation data with magnitude and frequencies of floods and therefore deduced flood magnitude and frequency increases to be due to urbanization.

High intensity, short duration storms, or micro-storms may have some geomorphic impact in watersheds. However, their impact will be enhanced by alterations in land use. Orbock-Miller, 1993, observed that channel responses to land use changes were enhanced by a high number of high magnitude storms. These storms caused increases in annual precipitation and trends were reflected in the annual streamflow values. Micro-storms have the ability to trigger phenomenons such as muddy debris flows and avalanches in hilly terrain increasing sediment delivery to streams (Jacobson et al., 1989; Miller, 1990; Gryta et al., 1989). Bierman et al., 1997, has shown that hillslope erosion in northern Vermont was triggered by intense storms during the early Holocene period. Aggradation in alluvial fans were dated indicating that the highest rates of erosion were caused by land use changes from forested to agriculture in Vermont (early 1800s, post 1830 clearing was for lumber). Even though intense storms did increase sediment delivery significantly in the early and late Holocene, the greatest erosion changes were the result of land clearing (Bierman et al., 1997). Micro-storms can produce significant increases in erosion and sediment delivery to streams which in turn will cause geomorphic change, but these changes will be more drastic for developed than for undeveloped watersheds.

The degree of impact of a storm on an area can depend on the drainage basin size. Smaller watersheds are more susceptible to extensive damage caused by an intense storm. The slope and length of a basin can be expressed in ratio (length divided by slope) which correlates with lag time (Leopold, 1971). The slope decreases and the length increases as the drainage area decreases. Therefore, as the drainage basin decreases, the lag time is decreases and runoff from an intense storm event can be more detrimental thereby increasing the capacity to transport sediment. Sediment yield per square mile increases as drainage basins decrease in size (Leopold, 1971). The geomorphic effects of storm events are therefore related to the size of the basin in which the storm event occurs.

5.1.2 Gaps in Literature

The major gap in literature seems to be that land use or climatological studies relating to hydro-geomorphic patterns in New England are rather limited, especially in Vermont. Levels of land use change that cause an ecological or geomorphic response represent the major gap in the literature mostly because they are so difficult to measure. With little or no information on the natural conditions prior to land use changes in the northeastern United States, there is little or no information on the direct causes of hydrologic and geomorphic responses to land use or climatological changes.

5.1.3 Suggestions for Further Research

Due to the paucity of studies conducted in Vermont and the difficulty in discerning some of the causal links between land use change and aquatic ecosystems, there is a strong need for original research conducted in the Vermont region. There is considerable data which state and federal agencies have collected on water quality and ecological conditions in the north east, but there are very few studies which have made links with this data and land use changes over time. One of the main goals of Phase II is to derive a threshold level of land use change where a significant hydrologic or geomorphic response would be expected. However, there are important considerations in defining ecological thresholds. Problems exist with trying to quantify this because one cannot equate floods with a threshold of land use change. Alterations in land use will cause increases in magnitude and frequency of floods, but to actually quantify the amount of change which will cause a flood is very difficult due to the variability of influences. For instance, one cannot expect a flood to increase Y amount from a clearing of say X acres. Therefore, to estimate a geomorphic threshold using an empirical field study approach, first study specific relationships of hydrologic change to geomorphic change must be fully documented in the literature. Due to the limited amount of hydro-geomorphic studies in Vermont, it would be prudent to gather more geomorphic data to be able to correlate with any changes in the watersheds, be they climatological or land use changes. Our specific recommendations are discussed in Section 7.0, Recommendations for Phase II.

5.2 Aquatic Ecosystems

Review of the current literature suggests that while ecological responses to land use may vary, some common themes emerge. The most consistent observation is that changing watershed landscapes from forest (the pre-disturbance landscape condition for Vermont, and for most of the mesic temperate zone) to agriculture or developed land increases the amount of nutrients and suspended sediments flowing into the stream ecosystem (Table 2). These effects are likely the result of two general mechanisms-1) increased runoff (see previous summary) and 2) decreased ability of the terrestrial ecosystem to retain both nutrients and materials. In addition to these general mechanisms of water quality change, decreasing forest cover appears, at least in some cases to reduce the ability of terrestrial ecosystems to retain other types of pollutants, such as heavy metals and Agro-chemicals (Munn and Gruber, 1991; Johneson et al., 1997; Stoeckel et al., 1997), and also to affect complex chemical transformations (Smith et al., 1997), which may affect overall water quality. The spatial scale of landscape change also seems to be an important determinant of water quality effects, as some studies demonstrated that land use throughout the watershed dominated water quality effects in streams (Allan et al., 1997), while others found that conservation or restoration of natural land covers in the riparian zone can help to alleviate watershed-level changes (Ormerod et al., 1993). Apart from forested watersheds, while some studies indicated consistent differences in broad land use categories (e.g. urban vs. agricultural) (Allan et al., 1997), differences between these land use categories themselves differed among studies, with some indicating more intense alteration under urbanization, and others under agriculture. Within these Major land use categories, different practices resulted in different effects. For example, several studies documented different effects of water quality under different agricultural uses (Johnes et al., 1996; Munn and Gruber, 1991). These studies draw attention to the importance of going beyond simple correlations between land use and water quality parameters, to mechanistic understanding of the effect of specific practices on nutrient and material exchange in watersheds.

A number of studies attempted to link the effects of changes in water and habitat quality with changes in fish and invertebrate populations and communities. Several of these studies generally found that changes in land use were associated with significant changes in biological communities. However, the nature and magnitude of these changes varied considerably among studies. There are several likely explanations for this variation. First, associations between land use and biological communities may be complicated by correlations between land use and underlying geological structure, making it difficult to determine whether differences in land use or differences in catchment geology were responsible for observed biological differences. Second, interactions between species, or confounding effects of other disturbances (such as exotic species introductions) may complicate the relationship between habitat quality and biological response (Crumby et al., 1990). Finally, the extent to which a landscape effect increases or decreases a biological parameter appears to depend on initial conditions. For example, land use which increases the transport of nutrients and sediments may increase total invertebrate abundance of species which can tolerate sediments and therefore use the increase in production associated with nutrient addition, while decreasing abundance of intolerant species, yielding little overall effect on invertebrate diversity (Lenat and Crawford, 1994). Similarly, land use effects in coldwater streams may reduce the abundance of coldwater species, but permit warmwater species to invade, increasing overall fish diversity (Lyons et al., 1996). Once again understanding the mechanisms of land use effects, along with the vulnerabilities and requirements of biological communities is key to accurately predicting potential land use effects for specific regions.

Two related topics were especially targeted as concerns for Vermont watersheds. These were the effects of micro-storm floods, a disturbance potentially associated with land use change, and channel dredging/alteration, a management technique used to ameliorate the negative effects of intense flood events. Studies which looked at effects of intense floods generally observed short-term decreases in fish and invertebrate abundance. However, in some studies, species seemed to recover rapidly from single events, and in one (Lobon-Cervia, 1996) were unaffected even in the short term. However, habitat quality was positively associated with the ability of a fish community to recover from flood disturbance (Pearsons et al., 1992), indicating that land use practices which decreased the availability of quality habitat may have negative impacts. In addition, these studies suggest that the appropriate scale to assess effects of floods is not in response to single events, but in response to changes in the magnitude, timing, and frequency of the entire flood regime. Dredging had either short-term negative effects with rapid recovery (Tikkanen et al., 1994), or had potentially long-lasting effects which were difficult to disentangle from other potential disturbances (Crumby et al., 1990; Barton, 1993). These results argue for studies which address larger spatial and temporal scales, and specifically identify the mechanisms underlying effects on biological communities.

5.2.1 Gaps in the Literature

As was the case with the hydrology/geomorphology literature search, a major gap in the ecological literature is a dearth of studies conducted in the New England region. This is particularly significant as running water ecosystems in Vermont encompass a wide range of conditions. For example, both coldwater and warmwater fish assemblages, as well as assemblages sharing species from both community types, are well represented in this region, and we have already discussed how land use effects may differ considerably between coldwater and warmwater communities.

A second major gap in the literature was due to a tradeoff between study depth and breadth. Detailed studies concentrating on particular effects tended to be short-term, and of limited spatial extent (one or a few streams). For example, studies looking at flooding effects tended to focus on single events, often in single streams. These studies provide only limited information on the long term effects of land use associated changes in flood regime on aquatic ecosystems. In contrast, broader-scale studies tended to encompass multiple effects, making it difficult to ascribe ecological change to any single effect.

6.0 CONCLUSION

Human-induced changes distributed throughout the watershed or focused within the riparian zone cause significant hydrologic, geomorphic, and ecological adjustments, and this ecological change can occur either directly or indirectly. For example, direct effects may result from the introduction of hazardous material into the stream that directly kills fish and/or limits their reproduction. However, other more indirect effects occur from watershed development and land use change that secondarily affect critical aquatic habitats (see Figure 3). Changes in the hydrologic regime by agricultural development, logging, and/or urbanization may cause significant geomorphic adjustments that alter and may degrade aquatic habitats -- thus limiting their distribution and abundance of valuable species (for example, native fishes), and altering key ecosystem processes such as nutrient cycling.

Our literature review has demonstrated that significant changes do occur to the physical and ecological characteristics of streams, but a simple uni-functional relationship between the magnitude of the disturbance and the magnitude of either the hydro-geomorphic or ecological response is difficult to establish. No two streams are exactly alike: they may differ in terms of geology, physiography, gradient, drainage area, position within the drainage network, and/or development history. Our literature review demonstrates that measurable impacts from development and land-use change will occur, but it is difficult to establish a specific minimum threshold for the magnitude of land use change that causes statistically significant hydrologic change and more importantly, the minimum specific hydrologic change that will cause statistically significant geomorphic and ecological change.

Considerable geomorphic attention over the past forty years has been devoted to establishing the role of extreme events in the context of major geomorphic adjustments. The search for geomorphic thresholds of channel de-stabilization was initiated by Schumm (1973) who documented that intrinsic or extrinsic thresholds explain why some extreme hydro-climatological events like a high intensity localized thunderstorm may have minor effects in one basin yet produce significant change in another basin elsewhere. Schumm indicates that the ability of an event, like a micro-storm, to produce a significant geomorphic change is due to a combination of the event's magnitude and also to the resistance thresholds of the natural system. There will always be some storm magnitude and intensity that will exceed the resistance thresholds of the stream system and/or watershed and thus cause natural geomorphic change. However the frequency of this de-stabilizing event is quite rare and infrequent. Land use change and development lower the resistance thresholds of the natural system and alter the natural magnitude-frequency relationship in such a way that the frequency of these de-stabilizing events is more common and that smaller magnitude events are more likely to trigger and maintain the de-stabilization. Also, it is very difficult to establish predictable thresholds may be for a given stream reach, and it remains uncertain what units (i.e., discharge, precipitation intensity, channel bed shear stress, etc.) should be used to categorize these thresholds. Although the specific, deterministic link between the exact level of land use change and the exact magnitude of hydro-geomorphic response is difficult to specifically establish, our literature review clearly shows that changes in land-use enhance the probability that catastrophic floods will occur. Development alters the hydrologic regime such that the magnitude-frequency relationship typical of undisturbed streams changes to produce more frequently occurring large floods and bankfull floods (see Figure 3).

7.0 RECOMMENDATIONS FOR PHASE II

Numerous techniques exist to express land use changes on streams and watershed conditions. Use of Geographic Information System (GIS) data and computer modeling to simulate pre-disturbance and post-disturbance can be effectively used in certain situations, but hydro-geomorphic characteristics and the resulting ecological responses are not as deterministic or uni-directional to generate the appropriate magnitude and sequence of events. Paired watershed studies can also be used to estimate the response of watersheds to measured levels of treatments, and in certain situations can be very effective (Hornbeck et al., 1970; Cheng, 1989). Paired watershed studies are the closest facsimile of a controlled laboratory experiment, but in order to minimize the "noise" of the experiment to make it more controlled, they are usually accomplished on small, steep watersheds -- typically of first through third order streams. The condition of these lower order streams differ considerably from the geomorphic and ecological characteristics of mid-to-higher order streams (e.g. Otter Creek, the Winooski River, etc.), and the "scaling up" and extension to these higher order streams may not be appropriate as the geomorphic processes of lower order streams (coarse caliber of bed material, dominance of debris flows and landslides, etc.) differ from the geomorphic characteristics of higher order streams that possess wider floodplains and flow on gentler gradients. Also, paired watershed studies are very expensive to establish and to monitor, and may not be of the appropriate time length to capture the necessary adjustments.

Although no two streams are alike, it does not preclude us from being able to establish similar tendencies or generalities. From a management perspective, an effective Phase II must be able to establish the current conditions of Vermont streams and also indicate what they should look like to function hydrologically and ecologically. Therefore, the approach taken for Phase II must establish the magnitude of hydrologic, geomorphic, and ecological conditions of both disturbed and undisturbed streams in Vermont. The perfect baseline situation or boundary conditions of undisturbed streams does not exist because anthropogenic landscape alteration has occurred since New England was settled and populated in the mid-17th century, and no information or data exists about the ecological or geomorphic characteristics of those previously undisturbed streams. It must be possible then to establish a surrogate for the baseline situation.

We advocate an array of approaches to establish the necessary thresholds of change to document major ecological and geomorphic adjustments to land use change. These approaches should: (1) be flexible enough to be embedded within, and take advantage of, the already existing robust data set from the various federal, state, and local agencies; (2) effectively capture the hydro-geomorphic and ecological conditions that already exist in streams in Vermont; (3) be of a type that can used as an effective baseline template for future studies to monitor adjustments over time; (4) and are robust enough to demonstrate and link geomorphic parameters to the ecological. We recommend that a successful Phase II component should focus on both a long-term and short-term perspective; should have a substantial field component; and should establish a methodology that already fits in with the methods and data that have been, and continue to be, collected by the various state agencies. In order to attain these goals, we suggest that Phase II should be a two-pronged approach: the first approach is a field component, and the second approach is based on already available data.

7.1 Field Component

We emphasize a field-based empirical state-of-the-art approach that is currently being used in both the aquatic ecology and fluvial geomorphology fields. Our recommended design is based on a habitat unit classification scheme initially developed by Bisson et al. (1982), Hawkins et al. (1993), and further modified by Bisson and Montgomery (1996). For data collection, we suggest that a detailed habitat unit classification scheme be conducted along a selected range of stream reaches: this approach will reveal the geomorphic characteristics, the ecological characteristics, and the links between the two (Figure 3). The habitat unit stream survey method is a way of measuring channel and bed characteristics at the "habitat unit" (HU) scale that is based on the geomorphic characteristics of the channel bed and on the hydraulic characteristics of the water surface (Hawkins et al., 1993; Bisson and Montgomery, 1996). Stream reaches of approximately 100-200 m should be selected for analysis, and field teams would then classify units along the reach as pools, riffles, glides, steps, cascades, etc. The dimensions of the habitat units (e.g. low flow width, bankfull width, depth, maximum pool depth, residual pool depth, habitat unit length) are measured along the reach, and it is therefore possible to determine for each reach the type, frequency, and dimensions of these geo-ecological bed and water surface characteristics. The frequency, depth and surface area of pools are critical variables influencing aquatic communities and ecosystems (Allen 1995), and therefore become a useful index of the geomorphic and ecological viability of specific stream reaches. Considerable research has shown that eradication of pools is one of the first "losses" associated with land use change and development (see Figure 3).

In order to establish the baseline conditions of Vermont streams and then to establish the magnitude of human induced impacts, we recommend that the habitat unit classification be conducted on numerous stream reaches of each of the following five conditions.

1. Undisturbed/"pristine" lands (e.g. Forest Service land)
2. Agriculturally-disturbed lands
3. Urban-disturbed lands
4. Lands that will soon be developed
5. Lands downstream of land soon to be developed.

We are advocating that one could use #1 above as a reference of what undisturbed streams would be like; and then use # 4 and #5 above as longer term studies to see what channel changes will occur during the "impact" stage. One can use #2 and #3 as an index of what "currently disturbed" stream reaches look like. More importantly, the data from short-term studies then can be used as a time-sub-zero baseline, and subsequent field analyses can then be used observed over time for the type, magnitude, and rate of geomorphic and ecological adjustments.

7.1.1 Establishment of Geo-indicators and Thresholds

The habitat unit classification method possesses the ability to establish minimum thresholds by determining the mean, range, and variance of specific bed types for "undisturbed" streams. The characteristics of the undisturbed streams can be used as an index of habitat unit types for streams in Vermont. The features of the disturbed stream reaches can be compared to the indices of undisturbed sections to determine (a) which components of the disturbed section are most out-of-phase with undisturbed sections, and (b) the magnitude of that difference.

7.2 Use of Existing Data

The habitat unit approach is becoming a widely used index in stream field studies as it roughly corresponds to both the geomorphic and ecological characteristics of streams. We believe that both short term and long term projects already exist in Vermont and that the necessary data for a significant portion of the analysis has already been collected -- but not compiled and analyzed. The Forest Service has collected considerable data of this sort, but it only extends to Forest Service land. However as part of Phase II, one can compile and analyze their data, and then extend their techniques for the type of streams (#2-#5) above. In addition to collecting data on the physical characteristics of undisturbed and disturbed streams, we recommend that ecological data also be collected and linked to the geomorphic data. This has rarely been done, and the comparison to disturbed and partially disturbed streams is very much what the project is about. A considerable data set on the hydrologic, geomorphic, and ecological condition of Vermont streams already exists. These data have been collected in various forms by various agencies in Vermont including: the United States Geological Survey (USGS), the Fish and Wildlife Service (FWS), the Forest Service (FS), and the Vermont Agency for Natural Resources (VANR), to name but a few agencies. We believe that these data provide an invaluable asset to Phase II. The contractor for Phase II must compile this diverse data set to determine the current geomorphic and ecological characteristics of Vermont streams. Much of the data exists in a form readily adaptable to the recommended habitat unit approach, especially the Forest Service data on undisturbed streams. The Forest Service has developed an extensive stream survey data base on streams in their domain and these data include habitat unit types, frequency, and condition. They also have categorized the distribution of large woody debris and have other ecological data as well.

7.2.1 Ecological Data

Habitat unit stream surveys can be linked to ecosystems and communities in several different ways. First, one can use published habitat suitability indices (HSI's) to assess differences among streams in their ability to provide suitable habitat for particular species. These indices have been developed for game fish species such as brook trout and smallmouth bass, and some non-game species. Second, one can compile existing data on study streams where available, or conduct our own biological surveys. Finally, it is possible to use standard community metrics developed by both U.S. EPA and Vermont Agency of Natural Resources to assess the biotic integrity of fish and macroinvertebrate communities in "undisturbed" vs. "disturbed" watersheds.

7.2.2 Hydrologic Data

Vermont has a very dense gage network monitored by the USGS with some of the oldest gages in the US. The data from these gages can be used to determine the changes in flood frequency occurring as a function of land use change and development. Also, regional relationships can be determined from these gages to be used in ungaged watersheds. The regional flood frequency relationships can then be used as a baseline threshold of "typical" conditions in Vermont, and the comparison of ungaged and developed basins to regional relationships can then help establish the magnitude of disturbance.

Data from USGS gages can also be used to evaluate the changes in sediment supply, and this can be accomplished for both suspended sediment discharge and for bedload as well. Some of the Vermont gages monitor suspended load, and these data can also be used to establish baseline thresholds. Although there is no monitoring of bedload, there are indirect ways to determine changes in bedload transport over time (see Lisle, 1981). The USGS periodically measures flow at its gaging stations to establish the stage-discharge rating curve, and they frequently measure the bed elevation. The shifts in bed elevation reflect the aggradation or incision occurring over time and are thus indicative of the watershed conditions upstream of the gage.

7.2.3 Establishing Geomorphic Thresholds of Development

Our literature review has demonstrated that significant changes occur in geomorphic variables during the extreme flows produced by land use change. It is very difficult to determine the link between the magnitude of land use change and the magnitude of geomorphic change. Geomorphologists have been extremely interested in the role of catastrophic floods and the link between flood magnitude and flood impacts. Surprisingly, there is very little correspondence between the size of the flood and it associated geomorphic impact.

Therefore, we recommend that before establishing the links between development and geomorphic adjustments, one must first establish the link between natural hydrologic relationships and geomorphic change. We suggest that two approaches be considered to provide the natural frequency of geomorphic change, and these different approaches be used to evaluate geomorphic change occurring due to micro-storm impacts at high elevation locations, and for geomorphic change occurring along alluvial floodplain stream reaches.

7.2.3.1 Micro-storms

Micro-storms are localized high intensity precipitation events that may be isolated or contained within larger frontal systems. They generally affect small, lower order streams of high elevation and are commonly associated with landslides, debris flows, and channel re-arrangement. Micro-storms and their associated impacts are natural processes. Large-scale impacts such as debris flows and landslides are relatively rare, and development tends to facilitate their frequency of occurrence by disturbing the natural rainfall-runoff relationship.

The first step would be to establish the natural frequency of micro-storms and their impacts in Vermont. This would entail a detailed field project to examine the post-Ice Age deposits in the high elevations for evidence of debris flows and landslides. Because the natural frequency of these events is so low, the historical period (post-1700 A.D.) may not contain sufficient evidence. These deposits would need to be field identified and dated (e.g. Radiocarbon dating), and then one can establish a natural frequency of debris flows. Once this baseline is established for Vermont headwater sections, it can be compared to developed sections to see if the frequency of disturbance has been accelerated because of land-use change and development.

The impact of a micro-storm decreases with increasing size of the watershed. For larger order alluvial streams there are a range of flood-producing mechanisms: rain,

rain on snow, snowmelt, and hurricane induced floods. Because of natural inherent thresholds and localized effects, there is no single discharge, or frequency of flow (e.g. 100-yr flood), that produces major geomorphic change. Geomorphologists have long noted that sometimes a large flood may be associated with major adjustments, and sometimes minor changes occur. For some sections of a watershed, the 50-yr flood will cause major change -- while for other sections the 200-yr flood generates no change. The lack of agreement results in part because the wrong units of observation are being used. Rather than discharge or flood frequency, geomorphologists are now indicating that units of bed shear stress be used to express the potential for geomorphic change. We recommend that a part of Phase II be devoted to going through the geomorphic literature dealing with large floods to determine if some minimum threshold of bed shear stress exists. If so, then it is possible to route different flow events through watersheds to establish the flow frequency of catastrophic floods.

The link to development and land-use change will be manifested through the shifts in flood frequency associated with development. If one can establish the natural frequency (i.e. 50-yr flood, 100-yr flood, etc.) of channel-de-stabilization from the geomorphic literature, then that becomes the baseline of natural disturbance. Because land-use change and development increases the frequency of large floods, it also increases the probability of attaining a de-stabilizing event. The shifts in flood frequency with development (either real or "modeled") can then be compared to see the rate at which this compares to natural disturbance.

7.3 Ecological Component

Ecological indicators and ecological thresholds are linked components in the assessment of land use change on stream ecosystems, which are also linked to the establishment of geo-and hydrological indicators. At the most basic level, a threshold can be defined as that magnitude of land use change which results in detectable change in some ecological parameter. There are several important considerations involved in defining this type of threshold. First, the ability to define a threshold of land use change for a given parameter depends critically on the amount of variation present in unimpacted, “natural” systems. Parameters which are naturally more variable make it difficult to separate “signal” (the effect of land use) from “noise” (natural variability). As many ecological variables exhibit considerable natural seasonal and spatial variability, this is a major concern. Second, the ability to define a threshold is influenced by the strength of the effects of land use, and the variability in this response. Parameters which are sensitive to change, and respond consistently to change, are good ecological indicators.

Because an ecological parameter is a good indicator, however, it does not necessarily follow that parameter response indicated as an unacceptable or threshold level of change. For example, change in the abundance of a single species may be sensitive to changes in land use, but if this species is not of immediate economic value, does not appear to play a major role in ecosystem function, and does not serve as a “flagship” for other important species or processes, it is difficult to maintain that changes in this bioindicator show an unacceptable threshold of land use change. To define this type of threshold requires “a priori” consideration of what is unacceptable. This decision involves not just scientific input, but input from the various stakeholders involved in any natural resource or land use issue. However, scientific input does have an important role to play. Ecological information can be critical in determining when changes in land use are likely to go beyond incremental changes in species abundance and distribution, and result in major ecological state changes, for example, a change from a warmwater to a coldwater fish community, or from a leaf-litter dominated to an algae-dominated stream ecosystem. In addition, understanding the ecological mechanisms underlying land use effects can help determine which ecological indicators are likely to be “leading-edge” or “early-warning” indicators of major changes to come.

The ecological component of a successful Phase II of this project requires that all of these issues be addressed. First, the sources, extent, and quality of existing ecological data which can be used to assess thresholds of detectable change, need to be clearly identified. Second, an analytical framework and design to use these data to test for effects of land use, and, when possible, to directly test the mechanisms responsible for change needs to be developed and clearly outlined. The development of new analytical techniques and approaches to test for the effects of land use has increased rapidly in recent years; the contractor for Phase II should demonstrate familiarity with these techniques, and the ability to apply them to critical natural resources problems. Finally, the successful respondent must clearly identify data gaps, and propose methodologies and conduct studies in order to obtain these critical data in the most economic and scientifically effective manner.

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TABLE 1

IMPACT MATRIX

A: GEOMORPHIC ADJUSTMENTS

Impacts	Channel Incision	Stream Width	Cross Sectional	Susp Seds	Bed Load	Over Bank	Sed. Yield	Riffle Pool	Sinuosity	Bank Erosion
Urbanization										
a. Minor (<5% developed)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
b. Moderate (5%-30% developed)	+	3(+)	3(+)	3(+)	+	+	3(+)	n/a	-	+
c. Major (>30% developed)	+	3(+)	3(+)	3(+)	3(+)	+	3(+)	n/a	n/a	3(+)
Logging										
a. Clear Cutting	+	+	3(+)	3(+)	3(+)	3(+)	3(+)	n/a	n/a	+
b. Road Construction	n/a	n/a	3(+)	3(+)	n/a	n/a	3(+)	n/a	n/a	+
Agriculture										
a. Forest to Agriculture	+	3(+)	3(+)	3(+)	+	3(+)	+	n/a	n/a	+
b. Pasture/Idle to Ag.	n/a	n/a	n/a	+	n/a	+	n/a	n/a	n/a	n/a
c. Ag. to Pasture/Idle or Forest	+	n/a	n/a	3(-)	n/a	n/a	-	n/a	n/a	-
d. Conservation Practices	+	-	-	3(-)	n/a	-	3(-)	n/a	n/a	-
Channelization										
a. Dredging (up,downstream)	+	+	3(+)	3(+)	-, +	3(+)	n/a	-	3(-)	+
b. Straightening (up,downstream)	+	3(+)	3(+), 3(-)	3(+)	-,2(+)	-, 3(+)	3(+)	3(-)	2(-)	3(+)

Key: + = increase - = decrease 0 = no impact 1 = minor impact (<15% change) 2 = moderate impact (15%-50% change) 3 = significant impact (>50% change)
n/a = not available

TABLE 1 (cont.)

IMPACT MATRIX

B: HYDROLOGIC ADJUSTMENTS

Impacts	Peak Discharge	Flood Magnitude and Frequency	Low Flow
Urbanization			
a. Minor (<5% developed)	2(+)	+	-
b. Moderate (5%-30% developed)	3(+)	3(+)	-
c. Major (>30% developed)	3(+)	3(+)	-
Logging			
a. Clear Cutting	3(+), 0(+)	3(+)	3(+), 2(-after 5 years)
b. Road Construction	2(+), 0(+)	2(+)	n/a
Agriculture			
a. Forest to Agriculture	3(+)	+	-
b. Pasture/Idle to Agriculture	+	+	-
c. Agriculture to Pasture/Idle or Forest	-	-	n/a
d. Conservation Practices	-	-	+
Channelization			
a. Dredging	+	+	n/a
b. Straightening (up,downstreaam)	-, +	-, 3(+) and for frequency 0(+)	2(+)

Key: + = increase - = decrease 0 = no impact 1 = minor impact (<15% change) 2 = moderate impact (15%-50% change) 3 = significant impact (>50% change)
n/a = not available

TABLE 1 (cont.)
IMPACT MATRIX
C: WATER QUALITY

Impacts	BOD	Nutrients	Hazardous Chemicals	Temperature	PH /Alkalinity /Hardness
Urbanization					
a. Minor					
b. Moderate	+	+	+		
c. Major					
Logging					
a. Selective Cutting			+		-
b. Clear Cutting					
c. Road Construction					
Agriculture					
a. Riparian Grazing		+			
b. Watershed Grazing		+			
c. Floodplain Farming		+			
d. Watershed Farming		+	+		+
Channelization					
a. Dredging					
b. Straightening					

Key: + = increase - = decrease

TABLE 1 (cont.)
IMPACT MATRIX
D: INVERTEBRATE

Impacts	Abundance	Diversity	Abundance of Sensitive Species	Biotic Integrity	Disease/ Deformity
Urbanization					
a. Minor					
b. Moderate	-	-	-	-	
c. Major					
Logging					
a. Selective Cutting					
b. Clear Cutting		-			
c. Road Construction					
Agriculture					
a. Riparian Grazing					
b. Watershed Grazing					
c. Floodplain Farming		-			
d. Watershed Farming	+	-	-	-	
Channelization					
a. Dredging				-	
b. Straightening					

Key: + = increase - = decrease

TABLE 1 (cont.)
IMPACT MATRIX
E: FISH

Impacts	Abundance	Diversity	Abundance of Sensitive Species	Biotic Integrity	Disease/ Deformity	Abundance of Game Species
Urbanization						
a. Minor			-	-		-
b. Moderate	±	±				-
c. Major						
Logging						
a. Selective Cutting						
b. Clear Cutting			-			-
c. Road Construction						
Agriculture						
a. Riparian Grazing						
b. Watershed Grazing						
c. Floodplain Farming						
d. Watershed Farming			-	±	+	-
Channelization						
a. Dredging			-			
b. Straightening						

Key: + = increase - = decrease

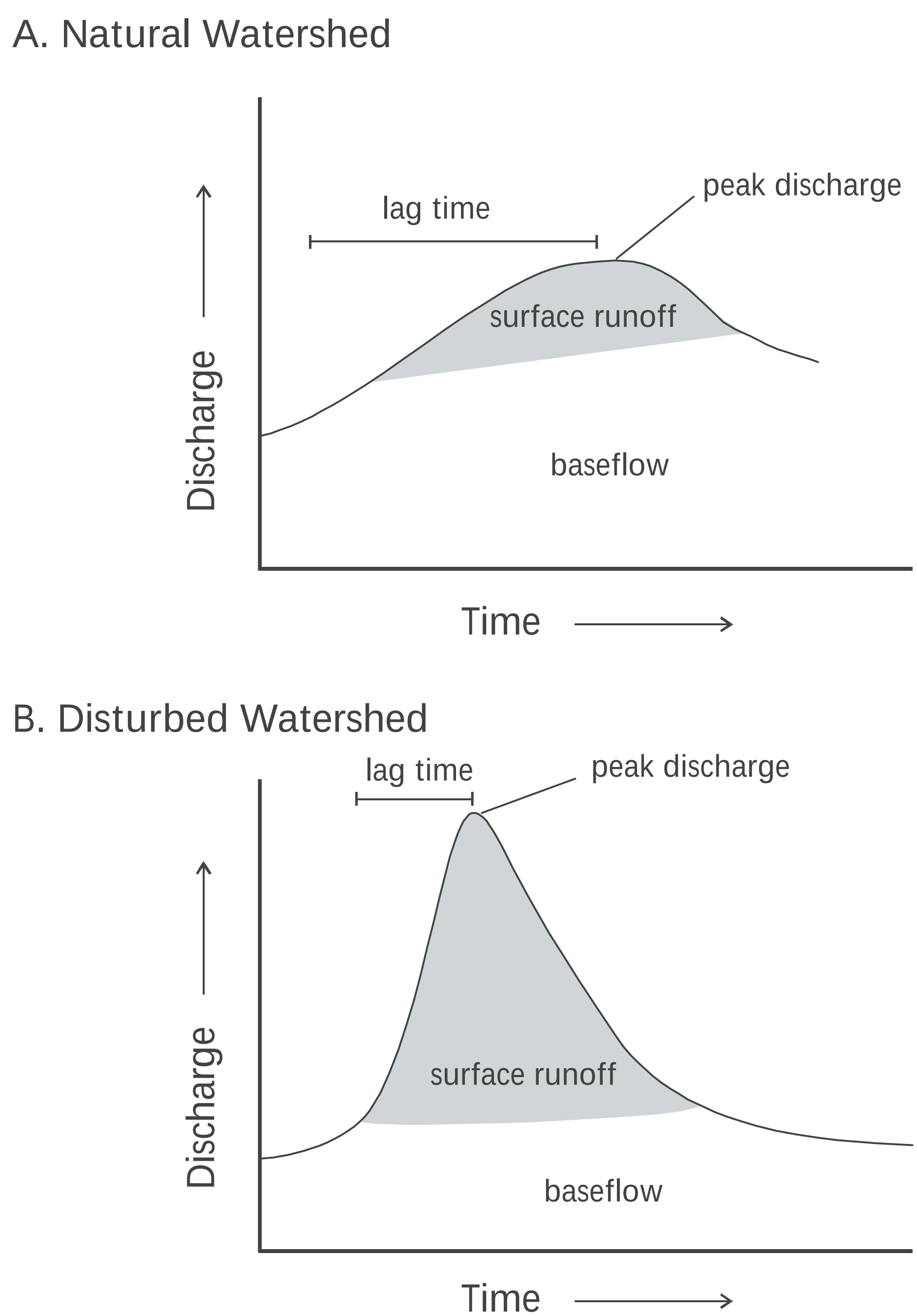

FIGURE 1: HYPOTHETICAL UNIT HYDROGRAPHS RELATING RUNOFF TO RAINFALL, WITH DEFINITIONS OF SIGNIFICANT PARAMETERS
Watershed Hydrology Protection and Flood Mitigation
Vermont Agency of Natural Resources, Waterbury, Vermont

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int:10-20-97 jms

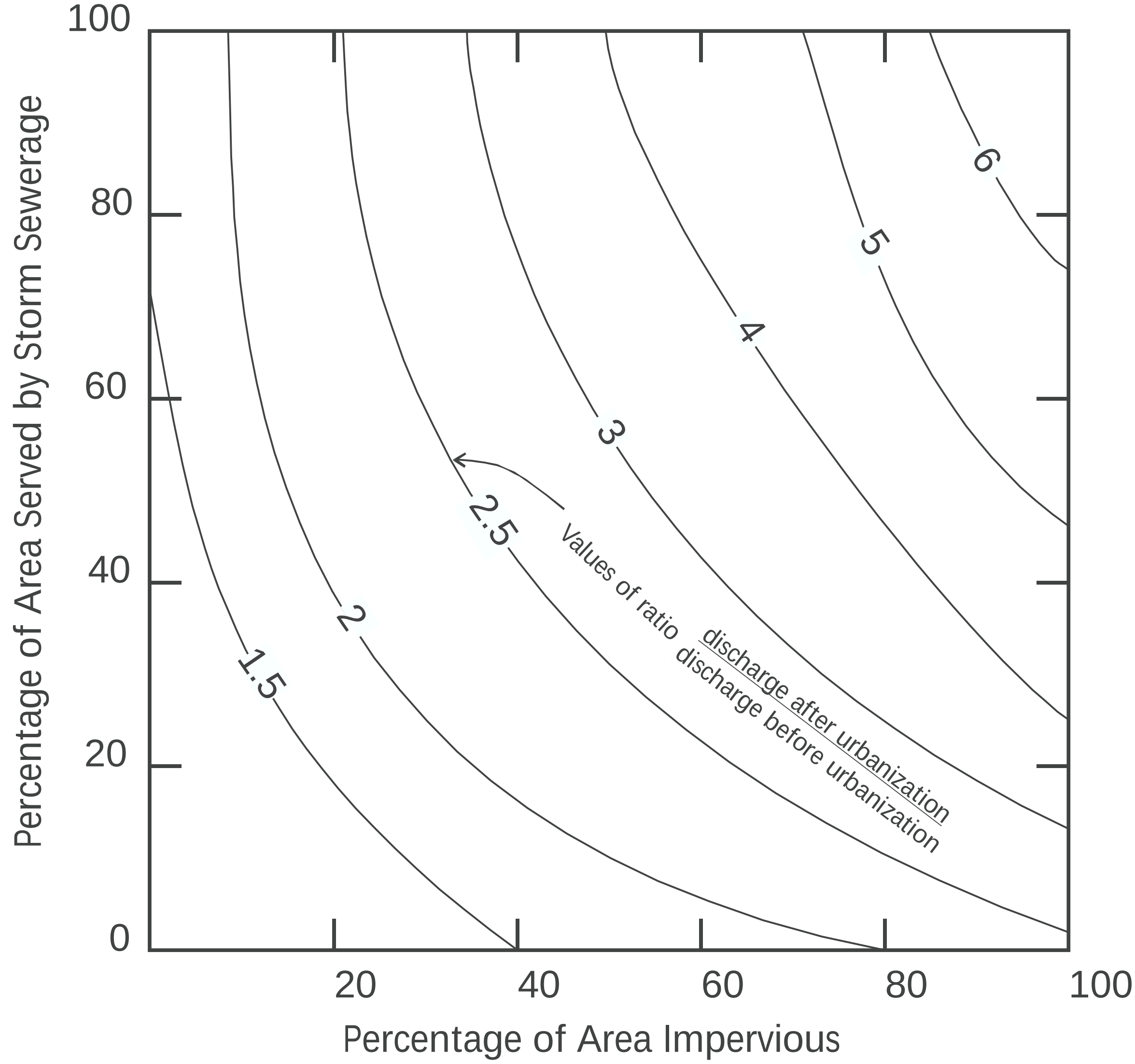

FIGURE 2: EFFECT OF URBANIZATION ON MEAN ANNUAL FLOOD
FOR A 1-SQUARE MILE DRAINAGE AREA
Watershed Hydrology Protection amd Flood Mitigation
Vermont Agency of Natural Resources, Waterbury, Vermont

Source: Luna Leopold, 1971.
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int:10-20-97 jms

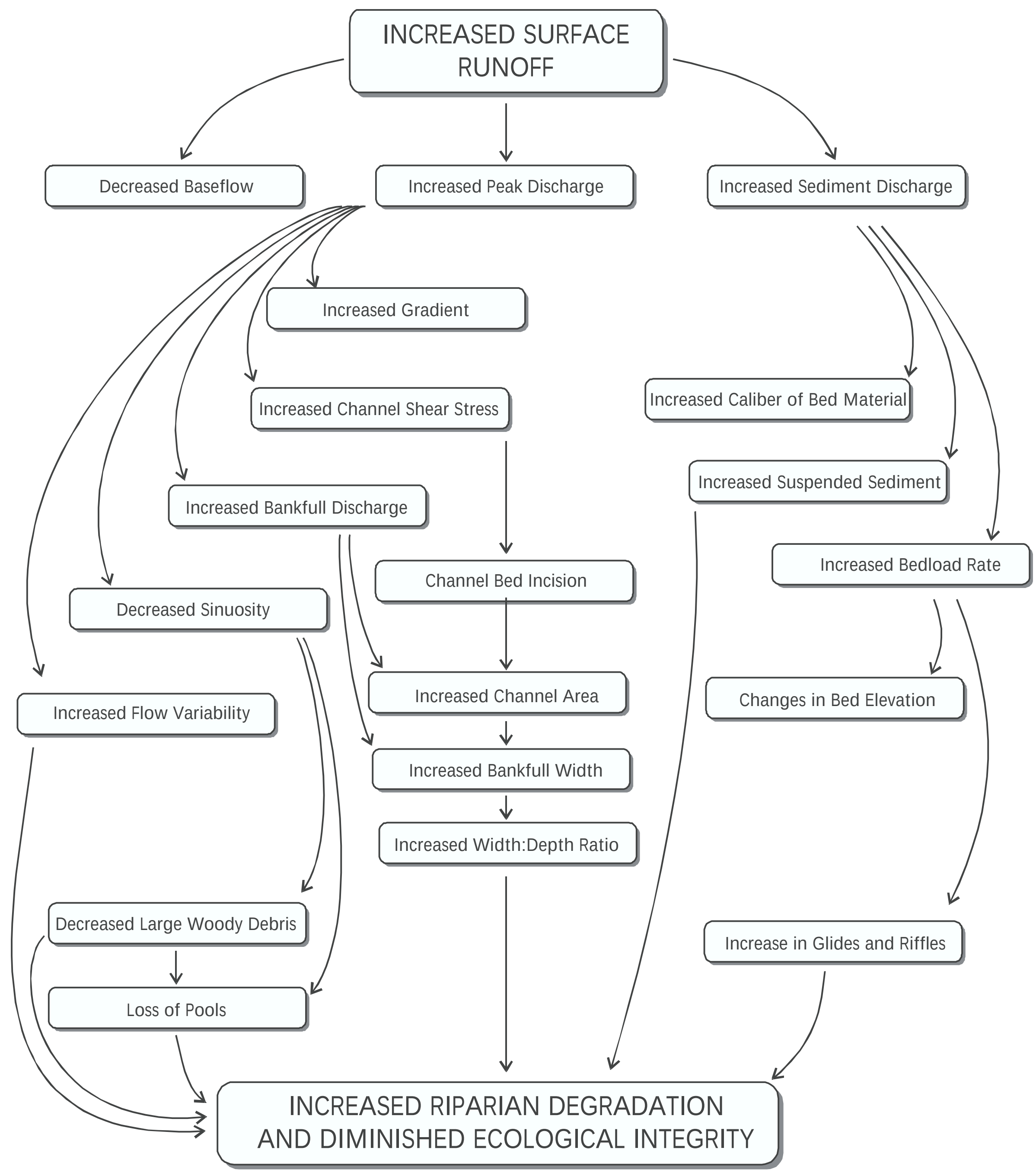

FIGURE 3: HYDRO-GEOMORPHIC ADJUSTMENTS TO LAND USE CHANGE
Watershed Hydrology Protection amd Flood Mitigation
Vermont Agency of Natural Resources, Waterbury, Vermont

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int:10-23-97; revl: 1-8-98 jms

APPENDIX 1- SUMMARIES OF TOWN INTERVIEWS AND DAMAGE SURVEY REPORTS

Town of Wolcott

History of Flooding: In the 30 years he has lived in town there has never been anything the magnitude of what occurred in 1995. He and the previous road commissioner felt there had been an "11 year frequency of flooding events" in the past with only minor damage.

The 1995 Flood: In 1995, 80% of the roads in Wolcott were affected by the flooding. This magnitude of damage could not be attributed to specific land use. However, there was a private dam on one of the streams that failed during the storm which certainly contributed to the magnitude of the damage.

Flood Mitigation: Under the FEMA program the Town was able to increase the size of the failed culverts and add wing walls. The integrity of the improvements made following the 1995 flood was maintained during the heavy rains of July 1997.

Avoidable damage: The road commissioner believes that the storms we have experienced in the past few years are "more violent" and that "perhaps this is the trend we have to prepare for". The road commissioner suggests having better control over beaver dams as a means of flood protect

Town of Worcester

History of Flooding: The two bridges which were lost in 1995 were 1900 vintage and had not experienced problems before. The road commissioner has lived in Worcester all his life and never experienced this type of flooding.

The 1995 Flood: There was a beaver dam ½ mile upstream of one of the bridges at the old mill site which failed during the storm contributing significantly to the volume of water in the stream channel. It is believed that a logging operation on one of the roads was the cause for flooding as the loggers had not cleaned up their landings and the skid road collected all of the water from the site and dumped it on to the town road.

Flood Mitigation: The Town had applied for a grant to perform some mitigation work as well as a grant for paving. They were denied the mitigation grant and awarded the paving grant.

Avoidable damage: The road commissioner agrees with the concept that the storms patterns are increasing in intensity. Perhaps better management of the logging operation would have prevented the flooding on that particular road. His observation is that the channels have been filled in over time. Swimming holes and fishing spots from the days of his youth are gone and there are many areas where the water runs just below the top of the bank of the stream. He believes that the streams need to be "cleaned out" to avoid future flooding.

Town of Hardwick

History of Flooding: Much of the flooding which had occurred in the past involved the Lamoille River in the Spring runoff times. The flood of 1995 was most serious in the tributaries to the Lamoille.

The 1995 Flood: The Kate Brook Road was extensively damaged and repairs cost approximately $250,000. Marsh Hill and Bunker Hill sustained damage and Tucker Hill was almost thrown up it was so badly damaged. There was a relatively large clearcut on the top of the hill immediately upgradient on Kate Brook Road in the area of West Woodbury. It is believed that this may have contributed to the flooding.

Flood Mitigation: Mitigation measures included rip rap, gabien baskets, stabilizing stream banks and roadbanks, and increased culvert size. These improvements were not disturbed by the heavy rains which occurred in July 1997. They are discussing replacement of the larger round culverts with box culverts and wingwalls. They have applied to NRCS for EWP money for more mitigation work but have been turned down.

Avoidable Damage: The Town Manager suggests that "cleaning out the streams, removing bars, would give the water some place to go".

Town of Underhill

History of Flooding: The Town representatives history with the Town was relatively short but he could state that the structures which had failed were 50 to 60 years old.

The 1995 Flood: Road construction and increased impervious surfaces were contributors to the flood.

Flood Mitigation: FEMA and town dollars were used to increase the size of culverts.

Avoidable Damage: No major land use changes were noted. The representative stated that hazard mitigation should be used proactively when repairs and replacements are made suggesting that this had been ignored in the past

Town of Middlesex

History of Flooding: The Town had suffered some damages in 1984 due to flooding but it was less intense than the 1995 event.

The 1995 Flood: The Macy Road in Shady Rill, Brook Road, and Center Road experienced the most damages during the 1995 flood event. A large culvert was completely obliterated on Center Road which had been in place for at least 20 years. No major land use changes were noted except that there has been an increase in the number of driveways particularly on the Macy Road.

Flood Mitigation: A larger culvert was placed on the Brook Road and was paid for by both FEMA and the Town at a 90%-10% match. Approximately 1½ miles of rip-rap was installed along the various brooks and streams. All work performed following the 1995 flood was intact following the rains of July 1997.

Avoidable Damage: The Road Commissioner suggests the streams be cleared of debris which take up space in the channel. This did not necessarily include dredging.

Town	Causes of Floods	Mitigation Measures	Avoidable	Other
Wolcott	private dam	increased culvert size	better control over dams, upgrade roads as new homes built	"we are experiencing larger, more violent storms than ever"
Worcester	poorly managed logging operation beaver dam	denied mitigation grant	need to clear channels, better control over logging operations	believes that storm intensities are increasing
Hardwick	increased number of homes on Bunker Hill Road, clogged ditches and culverts, logging operation,	rip-rap, gabion, increased culvert size	clear channels and dredge streams, upgrade roads and clean ditches, better management of logging sites	Tucker Brook damage caused by a "small intense storm cell"
Middlesex	no particular causes	rip-rap, larger culvert	future floods could be avoided by cleaning channels of debris	
Underhill	impervious surfaces steep slopes	FEMA financed upgrades	substandard road design played a part in the damages	

DSR SUMMARY FOR THE TOWN OF WORCESTER

DSR#	DESCRIPTION	AVOIDABLE	CAUSE	AMOUNT
24804	Sediment deposition/debris	N	N/A	$1,445
24836	N/A	N	N/A	$0
24805	Road/Ditch/Culvert	N	N/A	$4,085
24806	Road/Culvert	Y	extremely undersized culvert	$3,233
24808	Road/Culverts	Y	extremely undersized culvert	$9,868
24809	Road/Culvert	N	N/A	$5,799
24810	Embankment Erosion	N	N/A	$20,060
24815	Road/Culvert	Y	extremely undersized culvert	$2,474
24816	Roads/Ditches	Y	road upgrade w/out adequate drainage stabilization	$2,108
24824	Road/Culvert	Y	inadequate structure	$20,159
24826	Bridge	N	N/A	$9,669
24827	Roads/Ditches	N	N/A	$9,931
24828	Roads/Ditches	Y	Road inadequately upgraded	$35,759
24817	Bridge	N	N/A	$111,395
	TOTAL INCIDENTS	14	TOTAL AMOUNT	$235,985
	TOTAL AVOIDABLE INCIDENTS	6	TOTAL AVOIDABLE AMOUNT	$73,601
	PERCENT AVOIDABLE	43	PERCENT AVOIDABLE	31

DSR SUMMARY FOR THE TOWN OF ELMORE

DSR#	DESCRIPTION	AVOIDABLE	CAUSE	AMOUNT
24721	Road/Culvert	Y	severly undersized pipe	$2,569
24722	Road/Culvert	Y	severly undersized pipe	$2,746
24723	Road/Culvert	Y	severly inadequate pipe	$4,437
24724	Road/Culvert	N	N/A	$2,280
24725	Road/Culvert/Ditch	N	N/A	$3,808
24726	Road & Ditch	N	N/A	$4,255
24727	Road/Culvert	Y	inappropriate curb cut	$2,919
24728	Bridge Approaches	N	N/A	$10,952
24729	Road & Ditches	Y	severly undersized pipe	$19,027
24730	Road/Culvert/Ditches	N	N/A	$7,219
24732	Debris	N/A	N/A	$0
24733	N/A	N/A	N/A	$0
24720	Road/Culvert/Ditches	Y	severly undersized drive culvert	$10,557
	TOTAL INCIDENTS	14	TOTAL AMOUNT	$70,769
	TOTAL AVOIDABLE INCIDENTS	6	TOTAL AVOIDABLE AMOUNT	$42,255
	PERCENT AVOIDABLE	43	PERCENT AVOIDABLE	60

DSR SUMMARY FOR THE TOWN OF UNDERHILL

DSR#	DESCRIPTION	AVOIDABLE	CAUSE	AMOUNT
25704	Road	Y	severly undersized culvert	$9,318
25705	Debris	N	N/A	$163
25706	Road & Embankment	Y	severly undersized culvert	$1,466
25709	Road & Ditches	N	N/A	$12,293
25710	Road/Culvert	N	N/A	$24
25711	Road/Culvert/Ditches	Y	severly undersized culvert	$12,894
25712	Debris/headwall	N	N/A	$10,725
25714	Emergency ops	N	N/A	$1,779
25713	Road/Culvert	Y	undersized pipe	$44,090
26324	Supplimental to 25713	Y	undersized pipe	$6,101
25708	Bridge	N	N/A	$50,860
26323	Supplimental to 25708	N	N/A	$16,611
25707	Bridge	Y	Inadequate structure	$68,678
26322	Supplimental to 25707	Y	Inadequate structure	$4,961
	TOTAL INCIDENTS	14	TOTAL AMOUNT	$239,963
	TOTAL AVOIDABLE INCIDENTS	7	TOTAL AVOIDABLE AMOUNT	$147,508
	PERCENT AVOIDABLE	50	PERCENT AVOIDABLE	61

DSR SUMMARY FOR THE TOWN OF WOLCOTT

DSR#	DESCRIPTION	AVOIDABLE	CAUSE	AMOUNT
26039	Road & Ditch	N	N/A	$386
26041	Road & Ditch	N	N/A	$402
26042	Road & Ditch	N	N/A	$3,983
26043	Road & Ditch	N	N/A	$1,660
26045	Road & Ditch	N	N/A	$11,596
26047	Embankment erosion	Y	inadequate road const.	$7,666
26048	Undersized bridge	N	N/A	$5,580
26051	Road/Retaining Wall	Y	dam failure	$16,642
26056	Embankment erosion	N	N/A	$5,872
26058	Embankment erosion	N	N/A	$5,952
26060	Embankment erosion	N	N/A	$4,500
26061	Embankment erosion	N	N/A	$4,500
26062	Embankment erosion	N	N/A	$24,532
26064	Road/Culvert/Ditches	Y	inadequate road const.	$9,326
26053	Ins Deduct	N	N/A	$1,000
26052	Rec Field	N	N/A	$10,900
26059	Bank erosion	N	N/A	$11,280
26033/24762	Road/Culvert/Ditches	Y	inadequate structure ,road const.	$29,997
26038/24761	Road/Culvert/Ditches	Y	inadequate structure ,road const.	$13,477
26040/24764	Road & Ditches	N	N/A	$1,758
26044	Road & Ditches	N	N/A	$3,388
26054	Embankment erosion	N	N/A	$3,916
26057	Embankment erosion	N	N/A	$9,612
26063	Embankment erosion	N	N/A	$7,180
26028	Road/Culvert/Ditches	N	N/A	$2,298
26036	Culvert	Y	inadequate pipe	$642
26031/90593	Road/Culvert/Ditches	Y	inadequate drainage, road const.	$55,374
24778	Embankment erosion	N	N/A	$5,556
24779	Embankment erosion	Y	inadequate road construction	$3,238
24780	Road/Culvert/Ditches	Y	inadequate pipe	$2,250
26037	Road/Culvert/Ditches	Y	inadequate culverts	$10,737
26034	Road/Culvert/Ditches	N	N/A	$7,131
26035	Road/Culvert/Ditches	N	N/A	$2,026
26065	Debris	N	N/A	$1,200
26026	Road/Culvert/Ditches	Y	priavte dam failure	$1,157
26029	Foreman	N	N/A	$3,989
26032/90598	Road/Culvert/Ditches	N	N/A	$8,532
26050/24763	Bridge	Y	private dam failure	$159,829
26030/24794	Bridge	N	N/A	$373,806
26049	Road & Culvert	N	N/A	$99,500
26055	Embankment erosion	N	N/A	
	TOTAL INCIDENTS	41	TOTAL AMOUNT	$932,370
	TOTAL AVOIDABLE INCIDENTS	12	TOTAL AVOIDABLE AMOUNT	$310,335
	PERCENT AVOIDABLE	29	PERCENT AVOIDABLE	33

DSR SUMMARY FOR THE TOWN OF HARDWICK

DSR#	DESCRIPTION	AVOIDABLE	CAUSE	AMOUNT
25971	Embankment erosion	Y	inadequate culverts	$13,648
25973	Road/Culvert	Y	inadequate culverts	$32,185
25951	Road/Culvert	N		$1,919
25952	Road/Wingwalls	Y	inadequate drainage structure	$5,192
25953	Road/Culvert	N		$2,604
25954	Road/Culvert	Y	inadequate ditch	$11,458
25955	Road	Y	inadequate ditch and drainage	$14,770
25956	Road	Y	inadequate ditch and drainage	$3,247
25957	Road	Y	inadequate road/ditches	$12,596
25961	Road	Y	inadequate road/ditch	$5,145
25962	Embankment erosion	Y	inadequate road/ditch	$4,484
25970	Embankment erosion	Y	inadequate road/ditch/embankment	$7,460
25972	Road/Culvert	Y	inadequate road/ditch/embankment	$21,825
25938	Rip Rap Erosion	Y	inadequate drainage structure	$480
25939	Embankment erosion	Y	undersized culvert	$1,658
25942	Paved Road	N		$3,634
25943	Road/Ditches	N		$4,761
25944	Road/Ditches	N		$1,685
25945	Embankment erosion	Y	inadequate ditches	$325
25947	Road/Culvert	N		$2,595
25948	Road	N		$6,908
25949	Road/Culvert	Y		$23,022
42646	Stone Wall	N		$145,963
25963	Road Wall Bridge	N		$43,240
42646	Stone Wall	N		$145,963
25963	Road Wall Bridge	N		$43,240
	TOTAL INCIDENTS	26	TOTAL AMOUNT	$560,007
	TOTAL AVOIDABLE INCIDENTS	15	TOTAL AVOIDABLE AMOUNT	$157,495
	PERCENT AVOIDABLE	58	PERCENT AVOIDABLE	28

DSR SUMMARY FOR THE TOWN OF MIDDLESEX

DSR#	DESCRIPTION	AVOIDABLE	CAUSE	AMOUNT
24792/24705	Road	Y	undersize culvert and inadequate rip rap	$65,909
26301	Rescue	N		$255
24701	Road/Culvert	Y	undersize culvert; flooded 1993	$2,727
24702	Road/Culvert	Y	undersize culvert	$5,425
24704	Stream crossing	Y	undersize culvert	$44,120
24706	Road	N		$10,307
24707	Road	N		$5,455
24709	Road/Embankment	N		$1,498
24711	Road/Embankment	N		$1,343
26305/26302	Road/Embankment	N		$2,565
24708	Road/Culvert	Y	undersized culverts	$16,658
24710/26302	Road/Embankment	N		$15,192
24712	Wingwall	N		$12,829
24751	Stream Approach	Y	inadequate road design; 1990 flood	$17,287
26302	Road/Embankment	N		$6,711
26307	Road/Culvert	N		$5,907
26308	Road	N		$912
26309	Road/Culvert	Y	undersize culvert	$8,922
26310	Road/Culvert	Y	undersized culvert	$14,685
26311	Road/Culvert	Y	undersize culvert	$14,465
26312	Road	N		$7,042
26314	Road/Culvert	N		$1,761
26315	Road	N		$6,848
26316	Road/Culvert	N		$4,120
26310	Road/Culvert	N		$14,685
26314	Road	N		$1,761
24704	Road/Stream crossing	N		$44,120
2942	Road/Stream crossing	N		$34,966
	TOTAL INCIDENTS	28	TOTAL AMOUNT	$368,475
	TOTAL AVOIDABLE INCIDENTS	9	TOTAL AVOIDABLE AMOUNT	$190,198
	PERCENT AVOIDABLE	32	PERCENT AVOIDABLE	52

APPENDIX 2- ABSTRACTS FOR HYDRO-GEOMORPHIC LITERATURE REVIEW

Urbanization

Criteria: Similar Impact
Relevance: The influence of urbanization on flood peak streamflow

Title: Effects of Urban Development on Floods in Northern Virginia
Author: Anderson, Daniel G.
Source: Water in the Urban Environment, Geological Survey Water-Supply Paper:C1-C22
Date: 1970

Location: Piedmont and Coastal Plain regions of suburban Washington D.C.
Land Use: Fairfax County, Virginia was largely rural prior to 1940. At that time, residential development began. At the time of the study, commercial and residential development were occurring.

Watershed Characteristics:

Land surfaces are less than 500 feet above sea level and are gently rolling. Runoff from this basin is collected in the Potomac River through smaller channels. Stream channels commonly fall over 15 feet per mile and smaller tributaries fall over 100 feet per mile. Average precipitation each year exceeds 40 inches. The climate is humid.

Objective and Methodology:

The purpose of this study was to develop equations, using basin characteristics, that 1)estimated the average size flood for drainage areas in rural, suburban, or urban conditions and 2)evaluated the effects of urbanization on floods of all sizes. The sample basins ranged from almost completely natural to completely paved with storm sewers replacing natural channels. Basin characteristics determined included basin area, lag time, percentage of basin area covered with manmade impervious surfaces, length of primary water course through basin, and basin slope. Basin area, impervious area, length of primary water course, and basin slope were all determined using aerial photographs or available maps. Lag time was defined as a function of the length and slope of the basin. Rainfall information from 81sites in the region was used in a multiple regression analysis to develop and test the equations. A flood frequency curve was developed based on recorded flood events. By defining the frequency curve as a ratio of the magnitude of the largest flood of the year divided by its average flood magnitude, a dimensionless curve was created allowing differently developed basins to be compared.

Results and Discussion:

The study indicated that urban and suburban development significantly affected the magnitude of flood peaks. Basin to basin variation in size of the average flood was determined to be a function of basin area, lag time, and impervious area. The effect of sewer installation increased flood peak magnitudes by a factor of two to three. A completely impervious surface increased the average flood by a factor of 2.5, decreased the effect of larger floods, and did not have a significant effect on the 100 year flood. The lag time was the basin characteristic most affected by urbanization. The lag time for a completely storm sewered basin was reduced to one-eighth the lag time of a natural system. The lag time for a basin with storm sewering of the tributaries only was about one-fifth that of a natural system. On small, steep basins, drainage improvements by storm sewering in some cases tripled the average flood magnitudes. Complete development of stream channels increased the average flood by a factor of nearly eight in some cases. The equations developed applied only to the Washington D.C. area but the general method may be used to estimate the average flood or peak flood magnitude for any area where the major floods result from rainfall.

Urbanization, Channelization/Dredging
Criteria: New England Example
Relevance: A northeast (Conn.) study on geomorphic change (in channel characteristics, channel pattern, erosion, and bedload) and upset in equilibrium due to urbanization causing increases in flood frequency and magnitude.

Title: Sawmill Brook: An Example of Rapid Geomorphic Change Related to Urbanization
Author: Arnold, C.L., P.J. Boison, and P.C. Patton
Source: Journal of Geology, 90:155-166
Date: 1982

Location: Sawmill Brook, Middletown, Connecticut
Land Use: 15% urban in entire watershed; 30% urban in study area in 1975
Watershed Characteristics:
Drainage area of 18 km^2; tributary of the Mattabesset River; 250 m relief with low drainage density
Soils: glacial till covered with clays at the mouth of the basin
Geology: basalt in headwaters, flows into sedimentary rocks
Precipitation: 1,280 mm average total annual; Average maximum monthly of 117 mm in March and 125 mm in November

Objective and Methodology:

The main objective was to document the effects of urbanization on stream pattern morphology and sediment transport due to declines in sediment yields and increases in stream runoff.

Land use changes were observed from topographic maps and aerial photographs.

Flow measurements were obtained by measuring water depths at a weir placed where an artificial channel of the Sawmill Brook connects with the natural channel. A current meter was also used for verification during low flow conditions.

Results and Discussion:

From 1934 to 1975, natural land (agriculture and forest) area declined from 75% to 31% while urban land use increased from 0% to 30% in the study area.

A section of a tributary of Sawmill Brook (Fall Brook) and a part of the Sawmill Brook have been channelized which impacted the bedload. These channels have hydraulically smoother cross-sections and longitudinal profiles than the natural channels.

Bankfull discharge (8 m^3/sec) was exceeded five times in winter/spring of 1977 in the lower reach of the channel below the channelized sections. Two of these flow times exceeded the mean annual flood (9 m^3/sec). Since there was no significant change in climatic conditions, the increase in peak discharges and flood frequency is attributed to the increase in impervious cover, storm sewer systems, and channelization.

Significant erosion (annual mean of 0.5 m) was observed just downstream from the outfall of the constructed storm sewers. The occurrence of older trees undercut at banks indicated previous bank stability which was disrupted meaning an increase in bank erosion.

Conclusion:

Based on the examination of the geomorphology, rapid urbanization increased both sediment and water discharge causing disequilibrium within the channel. Channels were probably widened during this time causing more sediment discharge and overbank deposition. When construction was over, the sediment yields declined, but flows remained high causing accelerated bank erosion and increased bedload downstream. The result was the formation of the braided channels to compensate the increased bedload.

Logging, Agriculture
Criteria: New England Example
Relevance: Examination of alluvial fans and ponds sediments to study hillslope erosion in Northern Vermont

Title: Postglacial Ponds and Alluvial Fans: Recorders of Holocene Landscape History
Author: Bierman, Paul, Andrea Lini, Paul Zehfuss, and Amy Church
Source: GSA Today, A Publication of the Geological Society of America, 7(10):1-8
Date: October, 1997

Location: Ritterbush Pond and Sterling Pond, Northern Vermont
Land Use: 80% clearcut prior to the Civil War. Deforested hillslopes were used for farming and grazing. After 1860, some reforestation began as farms were abandoned.

Watershed Characteristics:

Sterling Pond	Ritterbush Pond
Area 0.3km^2	Area 0.07 km^2
Elev. 917m	Elev. 317m
Max. Depth 9m	Max. Depth 14m

The drainage basins of both ponds are underlain by schist. The Sterling Pond watershed is gently sloping while the Ritterbush Pond is steeply sloping.

The fans are located on permeable river terraces or hillslopes covered by glacial till or lake sediments. All but one are grass covered. Most of the fan beds are poorly sorted with occasional thin layers of well-sorted gravel and black laminae (15% organic carbon).

Objective and Methodology:

The purpose of this study was to determine patterns of Holocene hillslope erosion in areas once covered by glaciers. Twenty-three alluvial fans in northwestern Vermont were excavated up to 4.5m deep and 14m long. Sediment cores were collected from Ritterbush and Sterling Ponds. Organic material was carbon dated. The pond sediments served as a continuous record of the basin while the alluvial fans recorded discrete events from single hillslopes. Terrestrial and aquatic plants have different isotopic signatures, therefore carbon dating was performed that allowed distinction between terrestrial and aquatic sediments

Results and Discussion:

Grain size analyses, sedimentary structure and examination of an active fan indicated that stream flows rather than debris flows were responsible for transporting most of the sediment to the fans. Radiocarbon dating of five fans showed that two fans began to aggrade during the early Holocene period (between 8350 and 8060 ^{14}C yr B.P., and between 7835 and 7360 ^{14}C yr B.P.), two began in the late Holocene (2500 and 1900 ^{14}C yr B.P.), and one aggraded over 4m during historic time (<100 ^{14}C yr B.P.). Estimated aggradation rates suggested that aggradation was rapid in the early Holocene period. The mid-Holocene period experienced soil formation and relatively little aggradation. In all the fans studied, poorly sorted sediment buries a distinct soil profile. This overlying sediment postdated European settlement and was attributed to land clearing for agricultural purposes.

The Sterling Pond sediment was relatively homogenous and showed little terrestrial sediment. Ritterbush Pond, in contrast, showed stratification which was explained by periodic terrestrial sediment input. These layers of terrestrial sediment were characterized by millimeter to centimeter thick layers of silt and sand. Five intervals of terrestrial sediment input were identified. The first interval occurred in the late glacial period, two occurred in the early Holocene period, and the final two occurred in the mid and late Holocene period.

The results of this study indicated that the hillslopes were more active in the early and late Holocene periods than in the mid-Holocene. Pollen and lake level data suggested a warmer, drier, and stormier climate in the early Holocene period than today. Intense storms in the drier climate caused hillslope erosion in early Holocene time. The climate in the mid-Holocene period was cooler, moister, and less stormy, producing a more stable landscape. A change in the climate occurred again about 2500 ^{14}C years ago which was about the time terrestrial deposition again showed up in Ritterbush Pond sediments. In the past 200 years, changes in tree cover, contributed to hillslope erosion. In Vermont, land clearing and agricultural land use increased the sediment yield. The rates of aggradation in the alluvial fans studied were higher in the past 200 years than in the last 8000 years. This conclusion was enforced by the volume of alluvium and meander migration of the Winooski River delta following land clearing in the early 1800s. The Winooski River delta retreated and sediment delivery to the river decreased in the late 1880s indicating restabilization of hillslopes following reforestation.

Urbanization

Criteria: Similar Impact
Relevance: Effect of urbanization on stream channel incision

Title: Stream-Channel Incision Following Drainage-Basin Urbanization
Author: Booth, Derek B.
Source: Water Resources Bulletin, 26(3):407-417
Date: June 1990

Location: King County, Washington, located just west of the Cascade Foothills
Land Use: Rapidly urbanizing at time of study, 1985

Watershed Characteristics:
This region consists of primarily low-permeability till, lacustrine deposits, and bedrock. At the time of the study, this region was characterized as having 6% effective impervious area (EIA). Generally, low precipitation intensity allows canopy interception to play a significant role in the hydrologic balance. For this reason, infiltration capacities of undisturbed soil are rarely exceeded in this region. The largest runoff peaks occur during multi-day storms during which the groundwater table is raised high enough to cause runoff-producing saturated ground around streams.

Objective and Methodology:

The purpose of this study was to investigate the hydrologic changes brought about by urbanization. The Hydrologic Simulation Program FORTRAN (HSPF), a hydrologic model simulating runoff, streamflow, and channel routing, was used in this study. Multiple streamflow and rainfall gages in the King County basin were used to calibrate the model. Flood frequency and flow duration distributions were simulated for relatively low and high levels of urbanization.

Results and Discussion:

Modeling complete urbanization doubled flood flows and predicted a cross sectional area increase of 75%. The highly urbanized simulation (29% EIA), amplified major flood peaks and caused substantial runoff to occur in storms where, prior to development, no storm runoff was generated. The duration of peak streamflow from storms larger than the 2-year event, increased on average from 30 to over 100 times longer. Once channel incision had begun, it continued to occur in areas where channels were steep. Simulation of increased channel roughness, due to increased amounts of large organic debris (LOD) in the channel, reduced channel incision. However, an increase in large streamflows, due to urbanization, caused LOD to be washed away. Reduction in bed slope limited the transport of sediment and, as a result, the magnitude of channel incision that occurred. Terrain prone to channel incision exhibited characteristics such as low-order, high gradient streams, fine-grained noncohesive deposits, low infiltration capacities of upland soils, and channel form and gradient controlled by LOD. Recognition of these characteristics and appropriate planning prior to urbanization were sited as effective strategies in the mitigation of channel incision.

Urbanization

Criteria: Similar Impact
Relevance: Effects of Suburban Development on Flooding

Title: Magnitude and Frequency of Floods in Suburban Areas
Author: Carter, R. W.
Source: Geological Survey Research, USGS Professional Paper, 424-B, p. B9-B11
Date: 1961

Location: Washington, D. C.
Land Use: Suburban
Watershed Characteristics: Percent impervious area relatively low (note date of paper)

Objective and Methodology:

In order to measure the effects of development, the author examined two basic elements of hydrology: infiltration as a function of impervious surface area and lag time between rainfall excess and flood hydrograph. The effect of impervious areas on flood peaks is based on four assumptions; an average rainfall-runoff coefficient of 0.3, the effects of the change in impervious area is independent of flood magnitude, 75 percent of rainfall on impervious area reaches the stream channel, and the impervious area consists of many small areas randomly distributed throughout the basin. Lag time is represented as a function of slope(S) and length (L) of the reach: $L/\sqrt{S}$.

Results and Discussion:

The lower limit of the relation between lag time to $L/\sqrt{S}$ was defined by completely sewered basins. Partly sewered basins where the principal channels have been maintained in their natural state showed intermediary lag times. Lag times were observed to be much greater for those basins with natural channels. The effect of change in lag time for a recurrence interval of 2.33 years with an increase in impervious area of 12 percent resulted in a ratio of 1.8. This ratio is believed to be the maximum effect of complete urban development on flood peaks of any recurrence interval for drainage basins larger than 4 square miles in the Washington, D. C. area.

Logging
Criteria: Similar Impact
Relevance: Provides a paired watershed example to assess effects of logging on streamflow quantity and timing in larger (> 10 km²) disturbed vs. undisturbed watersheds.

Title: Streamflow Changes After Clear-Cut Logging of a Pine Beetle-Infested Watershed in Southern British Columbia, Canada
Author: Cheng, J.D.
Source: Water Resources Research, 25(3):449-456
Date: 1989

Location: Camp Creek, British Columbia, Canada
Land Use: Forested
Watershed Characteristics:
Camp Creek: Drainage area of 33.9 km^2; Precipitation: 600 mm; pre-logging water yield of 140 mm; median elevation of 1450 m
Greata Creek (control): 40.7 km^2; Precipitation: 550 mm; pre-logging water yield of 101 mm; median elevation of 1280 m
Half of precipitation is snow from Nov. through April
Soils: medium to coarse textured soils; igneous bedrock geology
Area logged: 30% of Camp Creek's drainage

Objective and Methodology:

The main objective was to compare streamflow changes in two watersheds (one control and one clear-cut) for pre and post logging periods. Variables looked at were annual and monthly flows, annual maximum daily peak flows and occurrence dates of annual peak flows, and annual half flow volumes.

Streamflow comparisons were made by conducting calibration regressions on streamflow data from the prelogging period with Camp Creek as the dependent variable and Greata Creek as the independent variable. Regressions and observed postlogging streamflow values for Greata Creek were used to predict values for Camp Creek if it had not been disturbed. Predicted and observed values were then compared. Differences in these values were attributed to logging.

Results and Discussion:

In the Camp Creek watershed, after logging streamflow changes observed were increases in annual and monthly water yields and earlier annual peak flows and half flow volume occurrence dates.

A water yield of 51 mm in the postlogging period for the control watershed revealed that the pre-logging period was considerably drier.

In Camp Creek, streamflows were significantly higher during the postlogging period than what was predicted using control watershed data. Increases in streamflows were observed in most months (except winter) with the most significant increases observed during the snowmelt season months of March and April. Another increase was seen in annual peak flows in Camp Creek for every year except 1978. There were also advancements of the peak flow and annual half flow volume occurrence dates. Differences between the control and logged watersheds were greater in the postlogging period compared to the pre-logging period.

The mean annual water yield of 29 mm was not that large compared to other studies which may be due to the small area logged (30%) or the drier postlogging climate. Besides the snowmelt season, the next largest percentage increase in streamflows occurred in July to August due to decreased evapotranspiration which resulted in increased soil moisture in the logged watershed compared to the control watershed.

Channelization/Dredging

Criteria: Important Concept
Relevance: Channel bed degradation as a result of gravel extraction

Title: Gravel Transport, Gravel Harvesting, and Channel-Bed Degradation in Rivers Draining the Southern Olympic Mountains, Washington, U.S.A.
Author: Collins, Brian D. and Thomas Dunne
Source: Environmental Geology Water Science, 13(3):213-234
Date: 1989

Location: Southern Olympic Mountains, Washington
Watershed Characteristics:
Humptulips: Flows along a gently sloping outwash plain
Wynoochee: Contains quantities of alpine outwash deposits below a dam which supplies gravel to the lower reaches
Satsop: Contains gravelly alpine outwash deposits

The three basins receive 3300 to 3800 mm annual precipitation

Objective and Methodology:

The objective of this study was to determine the approximate bed material flux for specific reaches of three rivers. Annual volumes of bedload transport were determined by three independent methods: (1) by using the Meyer-Peter and Parker bedload transport formulae; (2) by estimating bedload transport as a percentage of suspended load, measured previously by USGS on the Wynoochee and Satsop Rivers; and (3) by measuring rates of bed-material accretion at individual bars on six sets of aerial photographs taken between 1941 and 1985. Aerial photographs were also utilized to determine changes in channel width. Changes in channel storage were determined using trends from six USGS stream gauges. Attrition or reduction of bed material during transport was measured by laboratory experiment. To determine rates of gravel extraction a survey was conducted of gravel operations.

Results and Discussion:

Both the Wynoochee and Humtulips Rivers show a general downstream reduction in grain size reflecting the general decline in gradient. The declining grain size also supports the reduction of gravel in transit. The Satsop River does not show this relationship of grain size due to a relatively constant gradient. Rates of bar accretion and bank erosion were equal when averaged over each river. Gravel transport rates ranged from 1,900 m^3/yr to 5,000 m^3/yr on the Humptulip River. Attrition of gravel in the Humptulip River ranged from 14 to 40 percent at two points in the river. The transport of gravel was calculated as 4,000 m^3/yr in the Wynoochee with a 20 percent attrition rate. The best estimate of gravel transport on the Satsop River is 8,000 m^3/yr.

Response to the survey was limited so the survey results were supplemented by estimates of non-responding operators were derived by the Grays Harbor County Planning Department. While the data on gravel harvesting are incomplete it does indicate that there is a large discrepancy between harvesting and natural replenishment. On the Wynoochee River the extraction rate estimated through the survey was considered to be close to actual extraction rate. Since 1965 gravel removal has exceeded annual replenishment rates. The harvesting of gravel on the Humptulips River has exceeded replenishment with an estimated 80,000 m^3 removed in 30 years. The reported gravel extraction quantities for the Satsop River exceeded the calculated replenishment only during the period of 1978-1982. However, the unofficial estimates place annual gravel extraction rates at 15,000 m^3/yr beginning as far back as mid-1960.

The differences between supply and removal appear to have been accommodated by scouring of gravel from the channel beds which have been lowered at a rate of 0.03 m^3/yr.

Agriculture
Criteria: Similar Impact
Relevance: *Effects of agriculture on erosion and sedimentation*

Title: Effects of Agriculture on Erosion and Sedimentation in the Piedmont Province, Maryland
Author: Costa, John E.
Source: Geological Society of America Bulletin, 86:1281-1286
Date: September, 1975

Location: Western Run basin in the Piedmont region north of Baltimore, Maryland.
Land Use: The forested basin was cleared about 1750. Between 1800 and 1940, the land was used extensively for agriculture. In 1940, farming declined and reforestation and soil conservation practices were initiated. More than 80% of basin was forest, farmland, or pasture at the time of the study, 1975. The drinking water supply reservoir for the city of Baltimore lies 5 km downstream of the basin.

Watershed Characteristics:
Drainage area 155 km^2
Floodplains represent about 2% of the watershed. The soils generally consist of coarse clayey, sandy quartz overlain by gray to red-brown silt.

Management:

In response to heavy erosion due to agricultural land use practices, reforestation and soil conservation practices were initiated in 1940.

Objective and Methodology:

The purpose of this study was to determine the effects of agriculture on erosion and sedimentation in the Maryland Piedmont. A balance equation of sediment production and deposition since the onset of agricultural land use in the basin, was constructed from studies of surficial deposits. Mechanical analysis of the soil and land use history were used to estimate the amount of soil erosion of the area.

Results and Discussion:

Truncated Piedmont profiles implied about 0.15 m of soil erosion. Sedimentation in the reservoir indicated that 34% of the total eroded soil was carried out of the Western Run basin. Agricultural sediment, sediment deposited since the clearing of the forests and the initiation of agriculture, accounted for 14% of the total estimated soil erosion. Sediment resulting from agriculture was deposited by overbank deposition at highly variable rates. The remaining 52% of the eroded soil occurred as sheetwash deposits on hillsides and fan-shaped deposits at junctures of headwater tributaries. Sediment loads to the stream were reduced with the onset of soil conservation practices. As a result, channel scouring began to occur and was occurring at the time of the study.

Urbanization
Criteria: Similar Impact
Relevance: Effects of Suburban Development on Unit Hydrographs

Title: Changes in Character of Unit Hydrographs, Sharon Creek, California, After Suburban Development
Author: Crippen, John R.
Source: Geological Survey Research, USGS Professional Paper, 525-D, p. D196-D198
Date: 1965

Location: California
Land Use: Urban to Suburban
Watershed Characteristics: 245 acre basin of which 111 acres are developed of which 25 are impervious surfaces. Natural vegetation is grassland with scattered brush and trees.

Objective and Methodology:

According to unit-hydrograph theory, any excess precipitation will result in an outflow hydrograph that is proportional to the unit hydrograph. To observe any hydrologic changes after urbanization, this study measured peak discharge, unit peak discharge, time from centroid of excess precipitation to occurrence of peak discharge, time from centroid of excess precipitation to passage of 50 percent and 90 percent of runoff, and time between centroid of excess precipitation and the resulting runoff. Average 15-minute unit hydrographs for Sharon Creek were derived from storms of 1959-1960 which was prior to development and compared to storms for 1963 following a year of fairly stable land use.

Results and Discussion:

The magnitude of peak discharge in Sharon Creek increased as a result of the paving and drainage facilities from 180 to 250 cfs. Expressed as unit peak discharge the increase was from 470 to 653 cfs/mi^2. The time from the centroid of the excess precipitation to peak discharge did not change appreciably. The time for the centroid of the excess precipitation to pass 50 and 90 percent of all runoff were reduced from 54 and 145 cfs in 1959 to 38 and 92 cfs in 1963, respectively.

There is an 85 acre golf course within the basin which is irrigated with water from outside the basin. This artificial increase in baseflow should be subtracted but in this case it is fairly insignificant. The complicating factor is that the irrigation causes saturated shallow horizon conditions which decrease infiltration and cause a more rapid response of streamflow to precipitation and produces runoff after light storms which formerly would not have affected streamflow. This illustrates the complexity of water systems and how difficult it would be to look at the component parts of the basin.

Agriculture
Criteria: Vermont Example; Important Concept
Relevance: Examines the dynamics of overbank sedimentation in an agricultural watershed in Vermont

Title: Deposition of Sediment and Phosphorus within Three Floodplains of the LaPlatte River
Author: DeAndrea, P.
Source: M.S. Thesis, School of Natural Resources, University of Vermont, Burlington, Vermont
Date: 1994

Location: Hinesburg, Charlotte, and Shelburne, Vermont
Land Use: Forested (40%), agricultural (47%), and urban/residential (10%); dairy farming comprises 80% of agricultural land

Watershed Characteristics:
Drainage area of 1.4 km^2 and flows from the foothills of the Green Mountains to Shelburne Bay of Lake Champlain. Mean annual precipitation is 44.1^{N}F and mean annual precipitation of 33.7 inches.
Soils: glacial till and lacustrine sands, silts, and clays. About 20% of the watershed is steeply sloping, about 75% is lowlands with gently sloping topography, and the rest of the watershed is in a predominantly palustrine forested wetland area.

Objective and Methodology:

The main objective was to estimate the overbank deposition and associated sediment phosphorus concentrations in floodplains of the LaPlatte River during a snowmelt runoff flood event. Another objective was to observe whether differences in the three floodplain phosphorus depositions were correlated with differences in particle sizes and land cover type.

To carry out the objectives, a region was chosen within each floodplain to estimate sedimentation during one overbank flood event in the spring of 1993. Sediment catchment mats (SCMs), comprised of a plastic mesh made of roofing material called Roll Vent®, were attached to plywood and nailed into the ground surface to capture sediment normally deposited on the floodplain surface. The SCMs were flooded with overbank discharge during the 1993 snowmelt runoff and removed from the floodplain as soon as the floodwaters receded. The SCMs were returned to the laboratory to conduct analyses on amount of sediment deposited (using total suspended solids methodologies), particle size distributions of the sediments, and sediment phosphorus concentrations.

Results and Discussion:

The amounts of sediment deposited per unit area (g/m^2) were significantly different ($p < 0.10$) among all three floodplain regions. Mean areal sediment depositions in the three floodplains ranged were 1465, 7380, and 4953 g/m^2 (upstream to downstream). Where sediment deposition was low, the sediment contained a relatively large percentage of fine particles. Areas with high sediment deposition contained a large percentage of sand and a sufficient amount of fine sediment to influence total phosphorus (TP) deposition. High TP concentrations (mg TP/g sediment) were associated with fine sediments. The most upstream flooplain region exhibited sediment TP concentrations (mg/g) significantly higher ($p < 0.10$) than those downstream, indicating deposition of finer sediments upstream. Average TP concentrations of the sediment were 2.27, 1.71, and 1.62 mg/g (upstream to downstream), and TP depositions per unit area averaged 2.86, 10.1, and 6.55 g/m^2 (upstream to downstream). TP depositions were significantly different ($p < 0.10$) among all three floodplain regions, indicating that the greater meandering of the channel, the more deposition is possible and therefore serves as a greater nutrient trap.
Urbanization

Criteria: Important Concept
Relevance: Stream channel response to urbanization

Title: Patterns of Stream Channel Response to Urbanization in the Humid Tropics and their Implications for Urban Land Use Planning: A Case Study from Southwestern Nigeria
Author: Ebisemiju, Fola S.
Source: Applied Geography, 9:273-286
Date: 1989

Location: Elemi River basin near Ado-Ekiti, a major urban center in Southwestern Nigeria

Land Use: Rapidly urbanizing at time of study, 1988. Rainforest vegetation has been replaced with savanna woodland and grass on the steep slopes and with herbaceous vegetation on the lowlands.

Watershed Characteristics:
The town is underlain by coarse to fine textured tropical soils. The climate is tropical. Mean annual precipitation is 1367 mm (54 in.). The average monthly temperature is 25°C (77°F).

Objective and Methodology:

The purpose of this study was to determine if variations in downstream channel morphology and equilibrium state of the stream can be attributed to changes in land use patterns. The increase in channel capacity in downstream was compared to the increase in drainage area. Bankfull cross-sections and channel capacity were measured in the four natural and seven urbanized areas of the main stream. The drainage areas at the measurement stations were taken from topographical maps. Regression equations of drainage area versus channel capacity for the natural and urbanized areas were compared.

Results and Discussion:

The regression analysis showed that the natural areas of the basin were in equilibrium with the forest environment and that, with urbanization, each incremental increase in channel capacity was proportional to increases in streamflow. Some variability occurred in downstream channel capacity as drainage area increased in urban areas. This was attributed to sediment discharge to the stream which may decrease channel capacity downstream. Urbanization on steep slopes caused high rates of runoff and sediment yield. This caused disequilibrium in the stream. Urban development, along major roads where the channel banks remained forested, had moderate adverse effects on stream equilibrium.

Channelization/Dredging

Criteria: Important Concept
Relevance: Erosion caused by channelization thereby increasing stream gradient and flooding.

Title: Channelization: A Case Study
Author: Emerson, John W.
Source: Science, 173:325-326
Date: July 1971

Location: Johnson County Missouri

Objective and Methodology:

This report documents the increase in erosion caused by channelizing a stream thereby increasing its gradient. County Circuit Court records were researched to determine pre-ditching dimensions of the channel as well as the design dimensions immediately after construction. Length and elevation measurements for the former and present channels were made from topographic maps. Channel width and depths were made with tape and level.

Results and Discussion:

Before 1910, the Blackwater River had an average of 1.8 meanders per km with meander radius of 60 to 140 km. Prior to channelization the natural channel was 53.6 km long with a gradient of 1.67 meters per km. Bridge spans over the original channel were 15 to 30 meters. The new Blackwater channel was originally 9 meters wide at the top, 1 meter wide at the bottom, and 3.8 meters deep giving a cross-sectional area of 38 square meters. The present channel has increased in cross-sectional area ranging from 160 to 484 square meters. For the central part of the county the amount of erosion since channelization has averaged 1 meter per year in width and 0.16 meters per year in depth. The widening of the stream channel has resulted in the replacement of many bridges. In one case the same bridge has been replaced three times and finally collapsed because of continued erosion.

The downstream effects of channelization include increased flooding. The dredging of the Blackwater River was aborted near the Saline County line as the underlying bedrock made it economically unfeasible. Channel constriction at this point equated with a limited transport capacity. Above the county line, where the channelization occurred, the transport capacity of the river is 280 to 850 m^3/sec compared with downstream, where the dredging did not occur, the transport capacity ranges from 170 to 255 m^3/sec. Consequently flooding is extremely common with as much as 2 meters of deposition occurring over a 60 year period. Channelization allowed for use of more flood plain area however, there were significant social, economic, and environmental losses.

Urbanization

Criteria: Similar Impact

Relevance: Comparison of the effects of catastrophic flooding in rural areas to the effects of the same floods on areas under suburban development construction.

Title: The Urbanizing River: A Case Study in the Maryland Piedmont
Author: Fox, Helen L.
Source: Geomorphology and Engineering; Dowden, Hutchinson, and Ross, Inc., Stroudsburg, PA
Date: 1974

Location: Patuxent River Basin, Maryland. The river heads in North-central Maryland and flows to the Chesapeake Bay.

Land Use: 44% Forest or Swamp, 41% Agricultural, 15% Urban. Rapid conversion from agricultural to urban land use at the time of the study.

Watershed Characteristics:

Patuxent River Basin
Total Drainage Area: 2410 km^2
Main stream length: 177 km
Elevation 242m to sea level
Stream Gradients: 3.4 m/km in Piedmont to 1.9 m/km in coastal plain
Upland topography is hilly, valley to ridge relief is 9 to 15 m greater in Piedmont region than in coastal plain. Stream valleys in the upper basin are narrow, while valleys in the coastal plain are several thousand meters wide. Floodplains account for about 4% of the total area of the watershed, 95km^2. The soils are mostly silty and sandy. The surface of the watershed is moderately to severely eroded due to clearing and cultivation occurring since colonial times. The average amount of precipitation is 107 cm. The temperature averages 25°C in the summer and 2°C in the winter.

Objective and Methodology:

The objective of this study was to observe the effects of catastrophic floods and suburban construction on sediment transport and channel form in rural and urbanizing regions of the Patuxent River Basin watershed. Field data was collected at 36 locations in the Piedmont region and 11 locations in the coastal plain. All stations were located in the freshwater basin. Cross sections, channel parameters (width and depth), and bed material samples were taken two to four times. Suspended sediment samples were collected from October 1972 to January 1974 in a range of flows.

Results and Discussion:

The stream channels throughout the entire basin were widened as a result of flooding. On the average, width to depth ratios in rural channels increased by 47.5% and in urban channels by 70.5%. Stream beds in rural channels were coarsened by removal of fines, while urban channels were not cleared but developed new bars and dunes. Urban banks were more severely eroded than rural banks. Overall deposition along the floodplain was about 0.6 cm thick in most areas on average from each flood event. Although cross-sectional parameters continued to reflect the effects of flooding, rural natural channels recovered quickly. Lush vegetation regrew along the floodplain and sand and silt filled in the coarsened channel beds.

Urban channels behaved differently due to excessive (15 times more) sediment generated from urbanizing construction. This excess sediment filled local streams for about 5.6 km downstream of the sediment source. The deposition and scour occurring in the urban channels caused rapid changes in channel morphology. The length to width ratio increased and decreased as sandy bars continually built up and washed away. The channel stability observed in rural channels was not expected to occur in the urbanized channels until widespread construction ceased.

Urbanization
Criteria: Similar Impact
Relevance: Effects on channel networks of suburban development in a drainage basin.

Title: Network Characteristics in Suburbanizing Streams
Author: Graf, William L.
Source: Water Resources Research 3(2):459-463
Date: April 1977

Location: South Branch of Ralston Creek in Iowa City and Johnson County, Iowa
Land Use: Most of the land used for agricultural purposes until suburban development began in 1937.
Watershed Characteristics:

South Branch Watershed
Drainage area 7.7 km^2 (3 mi^2)
Relief ~40 m (130 ft)

The natural soil in the basin is primarily Kansan till, however soil development has been affected by about 40 cm (16 in.) of Wisconsin loess. The average annual rainfall in the area is about 81 cm (32 in.). The average annual temperature is 10°C (50°F). Natural vegetation dominated by hardwood forests with prairie openings. By the late 1800s, most of the land was used for agriculture. From 1937 to 1975, suburban development took place in a quilt work pattern.

Objective and Methodology:

The objective of this study was to determine the effects of the numerous artificial networks added to existing network channels when suburban development takes place. The study attempted to represent changes in channel network characteristics that occurred as a result of suburban development and demonstrate the effects of these changes on streamflow. Variables used to describe changes in the network were total number of network links, total length of exterior lengths, total length of interior links, and drainage density (total length/drainage density). Lag time and kurtosis, peakedness of the storm hydrograph, were the variables used to determine the effects of development on streamflow. The data were taken from historical maps and aerial photographs from 1937-1975.

Results and Discussion:

The total number of network links increased as new streets were added during suburbanization. The drainage density increased 50% as a result of the added length of the network. This denser channel network led to rapid collection of runoff and reduced overland flow. Long external links were divided into shorter internal links creating a more rectangular network and increased runoff due to the rapid incorporation of flow into the network. This rapid incorporation of flow reduced lag time and increased kurtosis, thus increasing flood potential.

Urbanization

Criteria: Important Concept
Reference: Demonstration of ways in which channel morphology can be identified

Title: Identification of River Channel Change due to Urbanization
Author: Gregory, K.J., R.J. Davis, and P.W. Downs
Source: Applied Geography, 12:299-318
Date: 1992

Location: Monks Brook, a tributary of the Itchen River, in south central England
Land Use: Largely agricultural until urbanization began in the 1930s
Watershed Characteristics:
Drainage area 41 km^2
Basin relief 140 m
The drainage basin is underlain by tertiary rocks with some chalk in the headwater areas.

Management:
As a result of residential development in the 1970s and 1980s, a 'greenway' corridor was created along the middle of the Monks Brook to protect from flood inundation.

Objective and Methodology:

The purpose of this study was to identify the distribution of channel morphology as a result of urbanization. Analysis of channel morphology was performed in three ways: 1)historical methods involving comparison of present morphological data with previously recorded data, 2)detailed field surveys of parameters such as channel width and depth, evidence of change such as vegetation or other structures in the stream, and 3)spatial variation in river channel changes using morphological characteristics, vegetation, and structures as indicators. Historical data was taken from large-scale topographic maps from 1866-96, 1933, 1951. The 1866-96 data predates any urbanization of the basin. The maps from 1931 and 1951 represent the first and second phases of urbanization that occurred in this basin. The field survey conducted for this study occurred in 1991.

Results and Discussion:

Using the historical method, channel widths were determined and compared. The average width of the channel increased significantly between 1931 and 1951 as a result of urbanization. The greatest width increase, 39%, occurs in the channels downstream of urbanization. An additional 18% increase in the average channel width occurred between 1951 and 1991. The average channel width upstream of urbanization did not change significantly between 1866 and 1991. Data gathered regarding lateral channel movement showed 11% of the channel realigned or straightened as a result of development, 23% had been modified by channelization and 66% had changed naturally through lateral migration.

A detailed field study, using a series of indicators, was also used to determine channel morphology. The measurement used was a channel width enlargement ratio, or the ratio of the new channel width to the channel width in 1866. Vegetation indicators, such as undercut banks and exposed tree roots, showed an average channel width enlargement ratio of 1.4. This was comparable to the map results. Structural indicators, such as protruding culvert outfalls and erosion behind embankment supports, suggested an average channel width enlargement ratio of 1.27.

Field mapping of the spatial pattern of channel adjustment indicated that 47% of the channel was enlarging in 1991. The enlargement varied from predominately vertical erosion (18%) to lateral erosion (14%) and a combination of the two (68%), showing that channel change does not take place equally along the entire stream.

Micro-storms
Criteria: Important Concept
Relevance: Factors affecting the distribution of debris avalanches

Title: Factors Influencing the Distribution of Debris Avalanches Associated with the 1969 Hurricane Camille in Nelson County, Virginia
Author: Gryta, Jeffery J., Mervin J. Bartholomew
Source: Geological Society of America, Special Paper 236:15-28
Date: 1989

Location: Nelson County, Virginia
Watershed Characteristics:
Area 622km^2
The Pedlar and Lovingston massifs make up this region. They are side by side along the Rockfish Valley fault. The Pedlar massif contains slopes greater than 25% on 91% of its terrain. Only 71% of the Lovingston massif has slopes greater than 25%. The Pedlar massif is made up of upper-granulite-facies metamorphic rock with mylonitic rocks present near faults. This formation is overlain by metabasalts, which form ledges and cliffs. The Lovingston massif is made up of lower-granulite-facies metamorphic rock interspersed with nonresistant, well-foliated, biotite-rich rocks.

Objective and Methodology:

The purpose of this study was to outline the area in Nelson County that experienced debris avalanches, determine density patterns of debris avalanches, describe debris avalanche frequency for bedrock units and determine susceptibility, and to explore the influences of rainfall, topography, and rock type on avalanche occurrence and chute orientation. Debris avalanche chutes were identified from aerial photographs and plotted on maps to assess regional trends and determine pattern density.

Discussion:

Hurricane Camille, which occurred in 1969, caused 1,107 debris avalanches in this region. The Lovingston massif produced 96% (high density) of the debris avalanches on 71% of its slopes. Based on a constructed rose diagram of chute azimuth data, 85% of the total chutes measured could largely be related to the intense rainfall associated with the hurricane. The remaining portion of the Lovingston chutes occurred on the east and southeast facing slopes. The Pedlar massif produced only 4% (low density) of the debris avalanches.

Most of the debris avalanche activity was contained within the 40cm rainfall contour, indicating that rainfall was a major factor in the determination of the low-density distribution of shallow landslides. High density debris avalanche activity was related more to topography within the biotite-rich rocks of the Lovingston massif.

Overall, in the bedrock units examined, about 88% of the chutes were influenced by rainfall, topography, and lithology. Approximately 10% were related to rock fabric. The authors concluded that debris avalanche susceptibility should be based on local relief and slope steepness, and frequency.

Urbanization
Criteria: Similar Impact
Relevance: Effect of urbanization on stream width

Title: Stream Channel Enlargement Due to Urbanization
Author: Hammer, Thomas R.
Source: Water Resources Research, 3(6):1530-1540
Data: December 1972

Location: Seventy-eight watersheds in the Pennsylvania Piedmont region, Philadelphia metropolitan area.

Land Use: Fifty of the basins contained some degree of urbanization such as large-scale residential, commercial or industrial development. Twenty-eight watersheds contained only rural land uses.

Watershed Characteristics:

Seventy-eight watersheds in the Pennsylvania Piedmont region were studied. The watersheds ranged in size from one to six square miles.

Objective and Methodology:

The purpose of this study was to determine the effects of urbanization on stream channel enlargement. Data collection involved the use of a grid system for each watershed. Each grid square, forty acres in size, was assigned thirty variables relating to land use and topographic characterictics. Channel width and depth were measured and cross sectional area was computed. A channel enlargement ratio (R)was calculated, as a function of the cross sectional area (C, ft^2) and the watershed area (A, mi^2), to be $C/28.4A^{0.657}$. This ratio is the cross sectional area of each stream, at the time of the study, as a proportion of the expected channel area prior to urbanization. This ratio was used to quantify the effects of different land uses within an urbanized basin, such as land in cultivation, wooded land, golf courses, housing areas greater than four years old, sewered streets greater than four years old, other impervious areas less than four years old, and open land. Averages for the enlargement ratios were used to summarize data.

Results and Discussion:

The impact of impervious development was directly proportional to the channel slope and the slope of developed land. Slope factors had a greater impact than the distance of developed land to a channel. Different impervious area land uses affected channel enlargement differently. Enlargement ratios for the land uses listed above were: land in cultivation (R = 1.29); wooded land (R = 0.75); golf courses (R = 2.54); sewered streets (R = 3.76-5.15); other impervious areas (R = 1.08); and open land (R = 0.90).

The impact of impervious areas on enlargement ratios associated with detached houses was small (R = 1.08)unless the gutters were connected directly to storm sewers(R = 3.36-4.15). The effect of streets and sidewalks was large if the street was sewered (R = 3.76-5.16) but small otherwise (R = 1.08). Contiguous impervious surfaces had a large effect (R = 6.26-7.99). The influence of impervious areas increased as the length of time that they existed increased (R = 4.16-5.16). Relatively low impacts were noted for housing and streets older than 30 years.

Logging
Criteria: New England Example
Relevance: Comparison of a disturbed watershed vs. an undisturbed watershed in relation to effects of logging on hydrology.

Title: Streamflow Changes after Forest Clearing in New England
Author: Hornbeck, J. W., R. S. Pierce, and C. A. Federer
Source: Water Resources Research, 6(4):1124-1132
Date: August, 1970

Location: Hubbard Brook Experimental Forest, West Thornton, New Hampshire.
Land Use: Forested and cleared northern hardwood forest.
Watershed Characteristics:

Watershed 1	Watershed 2
39 acres	105 acres
Avg. slopes of 20-30%	Avg. slopes of 20-30%
Avg. Precip. of 48-inches	Avg. Precip. of 48-inches
(1/4 to 1/3 as snow precip)	(1/4 to 1/3 as snow precip)

Soils are coarse-textured sands and sandy loams, derived from glacial till, with approximate depths of 5 feet.

Management:

The two study watersheds are operated as experimental, research areas of managed watersheds. The forest cover of Watershed 1 was cut and left in place so as not to disturb soil properties. Watershed 2 was used as a control area and remained forested.

Objective and Methodology:

The objective of the study was to obtain maximum streamflow during low flow periods by eliminating transpiration, and to see how clearing affects snowmelt runoff and nutrient cycling. Two similar watersheds were selected for the study, one was cleared of it's forest canopy and the other left intact. Clearing of the experimental watershed consisted of felling all trees, leaving them in place, and lopping all stems and branches greater than 3 feet above ground. In the cleared watershed, stump sprouts and ground cover growth were prevented by subsequent herbicide applications.

Results and Discussion:

The effect of nearly eliminating water loss from transpiration and water loss from canopy interception, greatly increased streamflow during the two consecutive years following clearing. During the first year, streamflow from the cleared watershed increased more than 40-percent that of the uncleared watershed.

Annual streamflow increases were greatest during the period of June through September with the cleared watershed having streamflow values 344-percent that of the uncleared estimate during the first year of study. Over a three year study period, increases were less than this due to differences in precipitation distribution. Recharges were similar during dormant periods when soil moisture recharge is a controlling factor in runoff.

The effect of clearing on snowmelt runoff was to advance cumulative runoff by 4 to 8 days during periods of major snowmelt.

The effect of clearing on flow duration was to increase duration at all flow levels. In addition, high flows for storm events greater than 20 csm showed increases ranging from 115 to 300% on the cleared watershed. These high flow changes occurred during the growing season from June to September. During the dormant season, changes were more erratic with relative change being fairly low.

Micro-storms

Criteria: Important Concept
Relevance: Effects of heavy rainfall on channel slope movements

Title: Slope movements triggered by heavy rainfall, November 3-5, 1985, in Virginia and West Virginia, U.S.A.
Author: Jacobson, Robert B., Elizabeth D. Cron, and John P. McGeehin
Source: Geological Society of America, Special Paper 236:1-13
Date: 1989

Location: Wills Mountain in the Appalachian Mountains, western Virginia and eastern West Virginia

Watershed Characteristics:

The dominant geomorphic form is folded and faulted Paleozoic sandstones. Most of the area is underlain by carbonates and overlying Reedsville Shale. These formations are covered by quartzite-rich debris. The climate is seasonal and temperatures are sensitive to elevation. The mean annual temperature and rainfall are 8.4°C (47°F) and 1,037mm (41 in.) at 930 m and 10.9°C (52°F) and 824mm (32 in.) at 580m.

Objective:

The purpose of this paper was to define conditions at which threshold movement occurred in regolith types ranging from calcareous marine shales to orthoquartzites. Threshold was defined in terms of the rainfall amount in a 2-day storm that would cause slope movement. The study also attempted to quantify slope movement susceptibility in terms of regolith, topography, land cover, and rainfall. Slope movement was defined as rapid mass movement of material. Slope movement was mapped from aerial photographs taken in April, 1986.

Discussion:

Tropical Storm Juan brought significant amounts of rainfall to the Wills Mountain area on November 4-5, 1985. Rainfall intensities of 10mm/h (moderate) or more were recorded for six hours. Rain fell continuously for more than 24 hours. Cumulative rainfall amounts ranged from 160mm (6.3 in.) to 240mm (9.4 in.). The antecedent soil moisture was high but not extreme. Streamflow was classified as moderately high.

Most of the slope movements occurred as shallow slips in thin colluvium of the Reedsville Shale. About 76% of those slope movements moved as muddy debris that eventually delivered sediment to streams or deposited sediment on terraces. Shale slopes that were mantled by ancient debris did not move. The majority of the remaining slope movements occurred in areas of limestone. These slope movements were characterized by large fractured blocks of limestone that became incorporated into mudflows and moved tens of meters downslope. Carbonates in the core of the mountain did not experience many slope movements due to the debris mantling which stabilized the slopes. Slope movements on the sandstone formations experienced small to moderate debris slide avalanches. Narrow avalanche scars extended down to first order streams. Eight large debris avalanches occurred on the sandstone formation.

Conclusion:

Previous studies indicated that large debris avalanches were triggered by high intensity, short duration rainfall events (2-day totals in excess of 200mm). However, the lower intensity, long duration storm of November 1985 caused numerous, smaller slope movements. Larger avalanche type slope movements were only triggered in areas which received rainfall amounts in excess of 200mm. The 2-day thresholds reached in the 1985 storm ranged from 170mm in the Reedsville Shale, to about 210mm in the Greenbriar Limestone. The authors stated that these thresholds could only be generalized for similar duration storms in a similar geological setting.

The sediment delivery to streams, when combined, was significant. Sediment was delivered both during and long after the storm. Mudflows deposited on terraces are susceptible to further movement from smaller storms. The paper stated that land cover is an important control on the spatial distribution of slope movement.

Logging
Criteria: Similar Impact
Relevance: Paired watershed studies examining the impact of land use change (logging) on hydrology, specifically clear-cutting impacts on peak flows before and after treatment.

Title: Peak Flow Responses to Clear-Cutting and Roads in Small and Large Basins, Western Cascades, Oregon
Author: Jones, J.A. and G.E. Grant
Source: Water Resources Research, 32(4):959-974
Date: April, 1996

Location: 3 Watersheds in H.J. Andrews Experimental Forest (Lookout Creek Basin) and 6 watersheds in the Cascade Range, Western Oregon
Land Use: Forested
Watershed Characteristics:
Watershed 1 - 1.0 km^2, Watershed 2 - 0.6 km^2, Watershed 3 - 1.0 km^2 : 60-100% slope, Upper Blue River - 119 km^2, Lookout Creek - 62 km^2, Salmon Creek - 313 km^2, N. Fork M. Fork Willamette River - 637 km^2, Breitenbush River - 280 km^2, North Santiam River - 559 km^2

Mean annual precip. 2300 at lower elevations - 2500 mm at higher elevations. Elevations 400 - 1200 m receive both snow and rain. Snow at higher elevations.

Geology: Tertiary and Quaternary volcanic rocks and some glacial deposits.

Objective and Methodology:

The objectives of this study were 1) to quantify long-term hydrograph changes related to clear-cutting and road construction and 2) to explain hydrograph changes by examining hydrologic mechanisms. The following factors were examined: 1) peak discharges associated with clear-cutting alone, road construction alone, or a combination of both 2) the influence of the size, season, and type of streamflow event and 3) if small-basin response to clear-cutting effectively predicts large-basin response.

Thirty four year records from two pairs of basins (60 to 101 ha) were examined as well as 50-55 year records from three pairs of basins (60 to 600 km^2). Of the above referenced watersheds, the three small watersheds in the Lookout Creek Basin (Watersheds 1, 2, and 3) were a paired experiment examining the changes in peak discharges between treated and control basins as a function of time before and after treatment. For the larger basins, there was no control basin available since all large basins in the northern Cascades have been harvested during this period. Three pairs of the large basins did have different land use histories. The difference in peak discharge between the more harvested and the less harvested basin was compared against the difference in magnitude of harvesting between the basins.

Results:

The Blue River/Lookout Creek basin pair had the most contrast in harvesting (in 1950s and 1960s 1% per year vs. $<0.25\%$ per year). From 1970 to 1990, this contrast reversed with 1% per year for Blue River and $<0.25\%$ per year for Lookout Creek. Road construction followed similar patterns to the cutting rates.

Watershed 1: After 100% clear-cutting there were a significant number of storms which had higher peak discharge, higher volume, advanced begin times, and delayed peak times. Also after clear-cutting, runoff events had higher than expected unit area peaks and higher volumes compared to pretreatment counts. Mean peak discharges significantly increased ($p<0.05$) in the first five years following clear-cutting and then increases declined after 6 years, but were still higher than pre-treatment. In the first five years after treatment, there were increases of more than 75% in mean peak discharges for small events but only 25% for large events. Six to 22 years post-treatment revealed that only fall and winter events had significantly greater mean peak discharges than pre-treatment.

Watershed 3: A significant number of storms had increased peak discharges and earlier begin times following road construction in 6% of the watershed, but increases were not significant in average peak discharges for the four year roads-only period. Following 25% clear-cutting with 6% already in roads, Watershed 3 showed storms with higher peak discharges, increased volumes, earlier begin times, and longer lasting storms. In the first five years, increases in peak discharges were observed by 50% as well as increases in begin times. Mean peak discharges declined 25 years later. Magnitudes of response of peak discharges were greater for winter/spring than for summer/fall events.

For larger basin pairs, the basin with the higher cumulative area clear-cut had significantly higher than expected numbers of storms with higher peaks. Basins with more rapid cutting rates also had significantly higher number of storms than expected with higher peaks. For matched storms, significant ($p < 0.05$) differences in the magnitude of the difference in unit peak discharges were observed, but correlations between discharges and cumulative harvest area are low. Blue River/Lookout Creek - little or no difference in harvest related peak discharges for events of differing sizes, seasons, or types. Salmon Creek/N. Fork Willamette - peak discharges with 5% more area harvested increased. Breitenbush/N. Santiam peak discharges with 4% more area harvested increased. Larger percentages of increase were observed in these last two basin pairs when the models were run using only large events and spring events.

Discussion:

Gradual recovery in peak discharges over time could be due to changes in evapotranspiration. Clear-cutting alone produced significant increases in small fall events and small to large winter events, but not large events alone. The addition of road construction to clear-cutting enhanced the water flow paths and increased channel delivery during storms. In Watershed 3, the 50-75% increases in winter and spring events can be explained by interception of subsurface flow paths. Also in Watershed 3, the rapid recovery of peak discharges over time compared to Watershed 1 can be a result of greater regeneration of conifers. Even though basins had differing characteristics, they had the same rate of response to cumulative cutting. When basins differed by 5% in cumulative area cut, there were differences in peak discharges.

Changes in land use could not be statistically tested as affecting peak discharges due to recovery of vegetation, ongoing land transformations, and small sample sizes.

The statistical analyses show that the large increase in peak discharges are attributable to the harvesting of forests in the Cascades of Western Oregon. The main cause of change is the increased drainage efficiency of basins due to the integration of a roads and clear-cut patches with the stream channels.

Logging
Criteria: Similar Impact
Relevance: The effects of logging and soil compaction in a watershed on stream flow characteristics.

Title: Logging Effects on Streamflow: Water Yield and Summer Low Flows at Caspar Creek in Northwestern California
Author: Keppeler, Elizabeth T. and Robert R. Ziemer
Source: Water Resources Research, Vol 26: no 7: pages 1669-1679
Date: July 1990

Location: North and South Forks of Caspar Creek, Jackson Demonstration Forest (approx. 11 km SE of Ft. Bragg and 7 km. from the Pacific Ocean).
Land Use: Logged in late 1800's, second growth regeneration.
Watershed Characteristics:

North Fork Watershed (Control)
483 ha
Elev. 37 to 320 m
35 % with slopes less than 30 %
7 % steeper than 70 %
Note: forest left intact

South Fork Watershed
424 ha
Elev. 37 to 320 m
35 % with slopes less than 30 %
1 % steeper than 70 %
Note: 67 % of forest volume removed

Topography ranges from broad, rounded ridge tops to steep inner gorges. Climate is Mediterranean with mild summers (10E to 25E C) and wet winters with avg. rainfall of 1200 mm (47 inches) per year. Soils are predominately derived from sandstone, and are well drained with high hydraulic conductivities.

Management: Both watersheds were clear-cut, logged, and burned in the late 1800's. Second growth stands of redwood and Douglas fir exist on the site now with some western hemlock and grand fir. During the study period, 67-percent of the forest volume of the South Fork Watershed was removed.

Objective and Methodology:

The objective of this study was to determine the effects of selective tractor harvesting of a second growth fir and redwood forest on the volume, timing, and duration of low flows and annual water yield. Stream gauging stations were placed on both forks in 1962 along with four rain gauges to measure precipitation. Both watersheds were monitored in undisturbed hydrologic conditions for four years.

Results and Discussion:

The study found that stream flow response to logging was highly variable. Total annual stream flow volume exceeded predicted values by 7 - 34 % in the logged watershed. The variable which most greatly impacted stream flow characteristics was total percent of watershed logged. In addition, the percent of watershed area compacted by roads, landings and skid trails was found to be the most important factor in determining annual flow volume differences between the logged and unlogged watershed. Annual flow volume on the logged watershed increased an average of 15 %, which was correlated to the 15 % of the watershed converted to roads, landings, and skid trails. The study suggested that removing the forest canopy resulted in greater soil moisture in the logged watershed which increased as the growing season progressed. Greater soil moisture resulted in decreased ability to absorb new precipitation. Therefore, mean daily flow rates increased in the logged watershed. This declined as regrowth progressed. The authors cite previous studies of the site indicating that increases in flow volumes resulted in 80 % sediment load increases with road building, and

275 % sediment load increases with logging.

Agriculture

Criteria: Similar Impact
Relevance: Effect of land use changes on stream channels

Title: Human Impacts on Wisconsin Stream Channels
Author: Knox, James C.
Source: Annals of the Association of American Geographers, 67(3):323-342
Date: September 1977

Location: Platte River Basin, Grant County, Wisconsin.
Land Use: Prior to 1830, the land was unsettled and consisted of forest (70%) and prairie (30%). At the time of the study, 1967 and 1971-1972, most of the natural land cover had been converted to fields and pastures.

Watershed Characteristics:
Drainage area 170 mi^2 (440km^2)
Local relief varies from a few tens of feet (5-15m)per square mile on the broad uplands to 500-600 feet (150-180m)per square mile adjacent to the larger valleys in the downstream portion of the watershed. Soils are predominantly silt over an organic-rich layer.

Management:
In the 1870s, corn was planted on steep terrain, causing severe runoff and soil erosion. Soil conservation methods were introduced in the 1950s. These practices have had an influence on surface runoff and sediment losses.

Objective and Methodology:

The purpose of this study was to investigate the impacts of land clearance and cultivation on erosion, sedimentation, and stream morphology. Vegetative and hydrologic characteristics of the watershed recorded in a 1832 land survey served as the baseline for the comparison to observed changes. Magnitudes of peak runoff for different land types were estimated using generalized equations.

Results and Discussion:

The peak runoff from a 2-hour storm event was estimated to increase by about three times between 1830 and 1967. Bank erosion and deposition, due to increased streamflows, were the principal causes of channel widening. Coarse bedload sedimentation consisted of between five and fifteen percent of the 1967 total sediment load in the Big Platte River while suspended sediment loads made up 85% to 95% of the total sediment load. Bedload sedimentation caused the wide and shallow channels along the first 25 miles of the river. High occurrences of overbank flows in the lower reaches of the Big Platte, due to Mississippi River backwater effects, caused accelerated sedimentation of suspended sediments and subsequently a narrowing of the river channel downstream of the 35 mile mark. Low flow channel widths increased since 1830 for sites in the watershed draining less than about 50 square miles. In most reaches, this increase was attributed to a natural response to the increased bedload sediment. In other reaches, this difference was attributed to lateral erosion of channel banks. Low flow channel widths decreased since 1830 for sites draining more than about 60 square miles. Low flow in these regions decreased as a result of increased surface runoff and decreased infiltration as land was cleared for agricultural use. The width to depth ratio of the channel increased as a result of increased agricultural land use for most reaches.

Agriculture
Criteria: Similar Impact
Relevance: Land use changes affecting geomorphology.

Title: Historical Valley Floor Sedimentation in the Upper Mississippi Valley
Author: Knox, James C.
Source: Annals of the Association of American Geographers, 77(2):224-244
Date: 1987

Location: Upper Mississippi Valley Lead-Zinc District
Land Use: Uplands mostly agricultural; pasture and woodland dominate the valley sides and floodplain
Watershed Characteristics:

Tributary - Doyle Site 1
27 km^2
Local relief of 55 m
Limestone and dolomite formations covered by deposits of loess
Mostly grassland prior to mining

Trunk Stream - Freese Site 2
450 km^2
Moderate to steep slopes with local relief of 80 m
Underlain by limestone and dolomite as well as small outcrops of sandstone and shale; covered by loess 2-3 m thick except where severely eroded on valley sides

Management: strip cropping, crop rotation in post-settlement time

Objective and Methodology:

The main objective was to evaluate trends in historical floodplain sedimentation and observe any correlation with anthropogenic influences after 1820. Four floodplain sites which were downstream from former lead-zinc mines were core-sampled for detailed analysis of trace metals in the sediments. Focus was on two sites: one a tributary and the other a trunk stream. Zinc analyses were used for dating the sediments since the zinc mining best represented the period of erosion and sedimentation. Textural analyses were also conducted to observe variations with particle sizes relating to the historical geomorphic events.

Results and Discussion:

At Doyle Site 1, acceleration of overbank sedimentation occurred as late as 1840. The average rate of Holocene vertical accretion was about 0.02 cm/yr which is much lower than the estimate of 0.29 cm/yr for the period before settlement of the area. Overbank sedimentation rates increased to 1.29 cm/yr after 1890 and then declined again to about 0.30 cm/yr after 1925. Overbank sedimentation at this site was reduced significantly since the 1920s probably due to the evolution of meanders following channel enlargement according to the author. At Freese site 2, high rates of sedimentation did not occur until the 1920s (3.3 cm/yr) and 1930s (4.5 cm/yr). After the 1930s, rates decreased to about 0.8 cm/yr. Coarser sediments in overbank sediments at site 2 represents the downstream response to more frequent and larger floods after upstream tributary channel enlargement.

The main cause of increases in overbank sedimentation in the lower valley was land use conversion from prairie and forest to agriculture. There was no correlation found between high rates of precipitation and high sedimentation rates. In the first few decades, the high rates were more likely a result of poor conservation methods. Improved land use practices such as strip cropping and crop rotation are probably responsible for the reduction in sedimentation rates back to pre-settlement values.

Urbanization, Channelization/Dredging
Criteria: Similar Impact
Relevance: Effects of urbanization and dredging on streamflow, suspended sediment concentration, and channel morphology

Title: Effects of Urbanization on Streamflow, Sediment Loads, and Channel Morphology in Pheasant Branch Basin near Middleton, Wisconsin
Author: Krug, William R. and Gerald L. Goddard
Source: USGS Water Resources Investigations Report 85-4068
Date: 1986

Location: North and South Forks of Pheasant Branch, Dane County, Wisconsin
Land Use: Agricultural and Urban

Watershed Characteristics:
Drainage area 24.5 mi^2
The North Fork basin has steep hills at the headwaters and flat areas downstream that have been dredged for agricultural use. These flat areas create a large natural flood plain. The South Fork basin drains an area of steep hills. At the time of the study, agricultural areas in the South Fork were undergoing urbanization. The stream flows through a marsh into Lake Mendota. The soils in Pheasant Branch are mostly silt loams. They are moderately deep, highly erodible in steep areas, and range from well drained to poorly drained.

Objective and Methodology:

The purpose of this study was to determine the effects of partial and complete urbanization on streamflow, sediment loads, and channel morphology. The current watershed characteristics were used to calibrate the model. Five gaging stations were installed in the basin in 1977. Three gages monitored rural runoff. Two gages monitored urban runoff and the effect of the marsh on reduction of peak flow and trapping of suspended sediment. Precipitation was recorded at three gages, suspended sediment was monitored at five gages. A rainfall-runoff model was used to determine the increase in flood peaks resulting from partial and complete urbanization of the basin. Channel surveys were conducted in 1971, 1977, 1979, 1980, and 1981. The channel width, cross-sectional area, and mean depth were determined.

Results and Discussion:

Partial urbanization increased the 2 year simulated flood by 320% in the basin in which urbanization was concentrated (South Fork) and by 32% in the more rural basin (North Fork). Complete urbanization increased the simulated 2-year flood by 360% in the South Fork basin and 220% in the North Fork basin. The rainfall runoff model showed an increase in flood events as urbanization increased and that smaller, more frequent floods increased more than large, infrequent floods.

The annual sediment loads were highly variable from year to year and were influenced by the magnitude and intensity of rainstorms. Storm intensity was more important than annual rainfall amounts in determining the sediment load. Storm runoff accounted for 82% to 99% of the annual suspended sediment load at one of the five gages for the period. The suspended sediment loads at the stations upstream and downstream from the marsh show different time distributions during storms indicating that the marsh is removing suspended sediment from the stream. However, during dry periods, suspended sediment concentrations downstream from the marsh were significantly higher than concentrations upstream. This indicates that suspended sediment was released from the marsh after storm events.

The cross sectional area of the stream increased 18% from 1971 and 1981. The greatest increase noted in cross sectional area, 28%, was caused by dredging in 1978. The urban reach of the stream was subject to visible erosion and deposition. Changes in channel morphology, as a result both partial and complete urbanization were predicted for the future based on generalized equations. These equations related forecasted flood magnitude to forecasted channel widening. The predicted percentage increase in channel width was 53% and 83%as a result of forecasted changes in hydrology from partial and complete urbanization respectively. These predictions were not validated with current data.

Agriculture
Criteria: Similar Impact
Relevance: Changes in channel erosion and sediment transport as a result of land use change.

Title: Effect of Land Use Changes on Sediment Transport in Goodwin Creek
Author: Kuhnle, R.A., R.L. Bingner, G.R. Foster, and E.H. Grissinger
Source: Water Resources Research, 32(10):3189-3196
Date: October, 1996

Location: Goodwin Creek watershed, Mississippi floodplain
Land Use: Agricultural (decrease from 26% to 12% in 1982 to 1990, respectively)
Watershed Characteristics:
Drainage area of 21.3 km^2. Upstream monitoring station area 17.9 km^2.
Soils are readily erodible silt loams. Topography contains small alluvial valleys and hilly uplands.
Hydrology: Flashy streamflow after storm events with rare overbank flows because of large channels. The flow inmost channels is ephemeral except in the lower reach where base flows occur all year.
Average annual rainfall: 1471 mm.

Objective and Methodology:

Flow was monitored and samples collected for suspended sediment at fourteen gaging stations located at flow structures beginning in 1981. Samples were taken in three different locations within the flow structure to calculate the fine, sand, and gravel transport. The two main parameters measured were sediment concentrations and depths of flow to correlate to flow discharge.

Land use was surveyed manually beginning in 1982 and put into categories of pasture/idle, forested, or cultivated. Most land use change which occurred was from cultivated land to pasture/idle land from 1982-1991. Management practices (soil preparation and planting, tilling and harvesting, and minimal soil disturbance in winter and spring) in agricultural land were conducted in the year used for the land use comparison. Sediment yield from the cultivated land was the focus since the yield from forest and pasture is generally low. The SWAT model was used to calculate sediment yield from upland sources (since the model does not account for channel bank erosion) and make comparisons were between land use and sediment transport in the watershed. Measured values were used as input parameters to the model, but GIS was used to develop curve numbers for runoff at other times.

Results and Discussion:

From 1982 to 1990, the percentage of land under cultivation decreased from about 26 to 12%. Measured fine sediment concentrations decreased 62%. There was a positive correlation observed between the percent of land cover under cultivation and the annual mean sediment concentration as well as the measured fine sediment concentrations solely for months April through July.

From the SWAT model and measured results, it was found that fine sediment concentrations from agricultural land accounted for 42% of the decrease in the total fine sediment concentrations and upland sources contributed 36% of the annual fine sediment load. Land surface disturbance through agricultural practices caused a higher correlation between the percentage of cultivated land versus the flow-to-rainfall ratio which provides a factor for channel erosion.

There was a high correlation between the product of peak runoff rate and volume and fine sediment yield from channel sources (measured minus simulated values). Sand concentrations were related to high flows. The concentrations of sand and gravel decreased (66% and 39%, respectively) during the period of study.

Changes in land use from cultivated to pasture/idle land therefore reduced flow rates which in turn affected the sediment yield for all particle sizes. The shift in land use was effective in reducing channel erosion and sediment transport by effectively reducing the amount of runoff leaving the upland areas more so than the reduction of upland sediment production.

Urbanization
Criteria: Important Concept; Similar Impact
Relevance: Changes in peak flows, overbank flow frequency, and sediment production as a result of urbanization.

Title: The Hydrologic Effects of Urban Land Use *In: Man's Impact on Environment*
Author: Leopold, Luna B.
Editor: Thomas R. Detwyler
Source: McGraw-Hill Book Company, New York, pp. 205-216
Date: 1971

Location: Maryland and Pennsylvania
Land Use: Urban
Watershed Characteristics:
Results of studies were extrapolated and interpreted to a common denominator of 1 mi^2.

Objective and Methodology:

The objective of this paper was to summarize effects of land use change particularly urbanization on hydrology. The hydrologic effects evaluated were changes in peak flow characteristics, total runoff, water quality, and channel characteristics (channel width, bank stabilization, erosion and scour, debris accumulation).

Studies by other researchers conducted in Maryland and Pennsylvania were reviewed and peak discharges of pre and post urbanization were compared by developing a ratio of the two conditions. Flood frequency curves were constructed for combinations of sewerage and impervious area percentages.

Results and Discussion:

As surfaces render impervious through urbanization, lag time (time interval between precipitation and runoff) decreases and the flood peak increases. Studies summarized revealed that the ratio of mean annual flood discharge after urbanization to before urbanization increased as the percentages of impervious areas and sewerage increased. The increase of this ratio indicates the increase of average annual floods due to urbanization.

Flood frequency curves showed that the most infrequent floods were not affected by areas which were heavily sewered or developed, but the frequent floods were affected. The more frequent floods were increased by smaller percentage ratios. Additionally, areas with greater impervious surfaces and sewers had more flows greater than bankfull discharge in a 10-year period.

Sediment yield in un-urbanizing watersheds is 200 to 500 tons per square mile on the average. Studies evaluated showed that sediment yield by urbanizing areas can be 10 to 100 times larger than rural areas and in some cases as high as 250 times. A major percentage of the sediment yield occurs during high flows which do not occur as frequently as other flows. Comparing rural versus urban sediment yield showed that a rural basin produces much less sediment (516 tons/year/mi^2) than an urbanized basin (3,220 tons/year/mi^2).

Since bankfull stage flow frequency increases with urbanization, the channel morphology is altered to have the capacity to carry the increased discharge, i.e., increased channel width and depth. Sediment yield can be increased as much as 5 times in the stream due to the increased erosion of bed and bank.

Agriculture
Criteria: Important Concept
Relevance: Geomorphic changes can affect the hydrologic regimes of riparian ecosystems which provide mechanisms for sedimentation and nonpoint source pollution.

Title: Managing Riparian Ecosystems to Control Nonpoint Pollution
Author: Lowrance, R.L, R. Leonard, and J.Sheridan
Source: Journal of Soil and Water Conservation, 87-91
Date: January-February 1985

Location: Little River, Tifton, Georgia
Land Use: Agricultural and riparian forest
Watershed Characteristics: Drainage area of 3,873 acres; coastal plain sediments

Objective and Methodology:

This article demonstrated the importance of riparian ecosystems (those areas along stream corridors) in their role to control streamflow, sediment deposition, and nonpoint source pollution in a watershed.

In the Little River watershed, inputs and outputs of a riparian zone were measured for suspended solids and nitrogen and phosphorus.

Results and Discussion:

The factors which help decrease nutrient output in the watershed are overbank sedimentation, streambank stabilization, and water temperature reduction be canopy shading.

As field runoff or flood waters enter riparian areas, water flow slows down and with this reduction in velocity, overbank sedimentation occurs and the water's erosive potential is decreased. If erosion is accelerated in the uplands from land use practices, the sedimentation in the riparian zone is therefore accelerated as well. Nutrients and other adsorptive pollutants are deposited along with clays in the sedimentation process leaving them less available for downstream transport.

In the Little River watershed, it was found that the riparian area was very successful at removing nutrients and suspended sediment (sediment delivery ratio decline from 5% to 1%). The flow from uplands was mostly subsurface flow. Surface runoff from uplands in general only occurs during rainstorms. In part, the removal of nutrients was related to the sediment deposition.

Riparian ecosystems control baseflow: if they are depleted, perennial streams can become intermittent.

Sediment concentrations in streams are better controlled if stream banks are stabilized because there is less bank erosion releasing sediments into the stream. Vegetation holds soil on a bank and also reduces velocity of water flow, enabling sedimentation and hence nutrient removal and storage.

Reduction in temperature occurs when the vegetation canopy is removed from stream banks. In turn, oxygen and nutrient levels are affected causing detriment to stream biota.

Agriculture
Criteria: Similar Impact
Relevance: Land use changes affecting geomorphology.

Title: Historical Valley Floor Sedimentation in the Galena River Basin, Wisconsin and Illinois
Author: Magilligan, Frank J.
Source: Annals of the Association of American Geographers, 75(4):583-594
Date: 1985

Location: Galena River Basin in Wisconsin and Illinois
Land Use: Uplands mostly agricultural; pasture and woodland dominate the valley sides and floodplain
Watershed Characteristics:
Drainage area of 526 km^2 which enters the Mississippi 16 km downstream from the Wisconsin-Illinois border.
Soils are mostly fine-grained with uplands covered by about 4 m of loess derived from glacial outwash.
Geology: sedimentary rocks of marine origin (sandstone, limestone, shale, and dolomite).
Stream gradient exceeds the rock dip in the upper and middle portions of the watershed, while the dip of rock exceeds the stream gradient in the downstream reaches of the trunk stream.

Management: strip cropping, crop rotation in post-settlement time

Objective and Methodology:

The main purpose of the study was to observe historical patterns of floodplain sedimentation and changes in the stream channel which were caused by post-1940 changes in agricultural land use and land management.

In the summer of 1979, 23 out of 37 original cross-valley surveys were resurveyed. Comparisons were made based on the same flow frequency, i.e., bankfull flow. Morphological breaks and point bar surfaces were used as a guide in selecting the bankfull channel. The range lines were surveyed and a minimum of 4 soil core samples were taken along each range line until the organic pre-settlement layer was reached. Surficial survey data was then plotted and a mean post-settlement depth of alluvium was determined.

Results and Discussion:

It was hypothesized that reductions in bankfull channel capacity were the result of decreases in the bankfull discharge and frequency of large flood events. There was a high correlation of drainage area and bankfull channel cross sectional area for the year 1979 indicating that the Galena River has adjusted to less variable flood conditions since 1940. Post-1940 improved land use practices have improved which resulted in decreases in peak discharges. This was demonstrated by the reductions in bankfull channel capacities and bankfull widths.

For the years 1940 and 1979, the magnitude of sedimentation increased in the downstream direction, i.e. as drainage area increased. Overbank deposition has decreased however since 1940. Prior to 1940, overbank sedimentation averaged 1.9 cm/yr and since then it averaged 0.75 cm/yr. Since 1940, sediment transport relative to sediment storage was more dominant while sediment yields have decreased.

It was shown that floodplain width affects the thickness of overbank sediments: the wider the floodplain, the thinner the sediments because there is more area for the energy of the flow to disperse. However, those unusually narrow valleys also showed small magnitudes of post-settlement sedimentation. It was also demonstrated that wider channel zones have more deposition while more erosion and sediment transport and less overbank deposition occurs in the thinner zones. The increase in erosion and transportation in thinner zones is due to the increased flow velocity and depth of the channel.

Urbanization

Criteria: Similar Impact; Similar Soils
Relevance: Effects of urbanization on small streams

Title: Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion
Author: May, Christopher W., Richard R. Horner, James R. Karr, Brian W. Mar, and Eugene B. Welch
Source: Watershed Protection Techniques 2(4):483-494
Date: June 1997

Location: Puget Sound Lowland Region
Land Use: Land use practices include timber-harvest, agriculture, and urbanization.
Watershed Characteristics:
Twenty-two small stream watersheds were used to represent a range of development levels, from relatively pristine to highly urbanized. All streams were third order or smaller. The basin areas ranged from 3 to 90 km^2 with headwater elevations less than 150 meters. The stream gradients were all less than 3.5%. All but three of the watersheds were dominated by poorly drained glacial till. The remaining basins were dominated by moderately well drained glacial outwash. Natural riparian integrity, characterized by wide buffers, a near continuous corridor, and mature coniferous forest, varied throughout the twenty-two watersheds.

Objective and Methodology:

The objective of this study was to identify linkages between landscape-level conditions and instream environmental factors. These factors include defining the relationship between watershed development and aquatic biota. The goal was to define a set of stream quality indices for managing urban streams. This study also set out to identify any thresholds of watershed development as related to instream salmonid habitat and aquatic biota. Watershed attributes were established using geographic information system (GIS) data, aerial photography, basin plans, and field survey. Impervious surface coverage, riparian integrity, instream physical habitat characteristics, water quality constituents, and aquatic biota were analyzed. Total impervious area (%TIA) was the primary measure of watershed development. Because calculating impervious surface area can be expensive, a lower cost alternative was investigated. Development was alternatively expressed as road density. Water quality monitoring of constituents, including total phosphorous and suspended sediment concentrations, was conducted at 23 sites on 19 streams and biological sampling occurred in 31 reaches of 21 of the streams.

Results and Discussion:

Watershed imperviousness ranged from $<5\%$ (undeveloped) to $>45\%$ (highly urbanized). Wide riparian buffers were found only in the less developed watersheds. Storm event mean concentrations of several chemicals were found to be related to storm size and total impervious area. Physical and biological characteristics such as the two year stream flood magnitude, riparian buffers, large woody debris (LWD), and benthic index of biotic integrity (B-IBI) changed most drastically during the initial phases of watershed development, as %TIA exceeded the 5-10% range. The two year flood streamflow increased as %TIA increased. As urbanization increased, the percentage of riparian buffer encroachment increased from 10-40%. Significant amounts of LWD occurred only in streams draining undeveloped basins. As the quantity and quality of LWD in streams decreased, habitat complexity decreased as well. Only undeveloped basins showed a B-IBI of at least 32 (45 is the maximum, 9 is the minimum). Urbanized basins generally maintained a B-IBI of about 15.

As development continued, the rate of degradation of both physical and biological characteristics became constant. Water quality constituents, such as intergravel dissolved oxygen (IGDO), and sediment concentrations did not follow the same pattern. These variables changed little until watershed development exceeded 40%. At no time in the study did water quality constituents surpass limits needed to support aquatic life. The authors suggest that resource managers must consider land-use controls, width of riparian buffers, and protection of habitat when taking measures to preserve stream systems.

Micro-storms
Criteria: Important Concept
Relevance: Effects of flooding on erosion

Title: Flood Hydrology and Geomorphic Effectiveness in the Central Appalachians
Author: Miller, Andrew J.
Source: Earth Surface Processes and Landforms, 15:119-134
Date: 1990

Location: South Branch Potomac River and Cheat River basins in the Central Appalachian region

Objective:
The purpose of this paper was to describe the November 1985 flood, compare it with other floods in this region, and attempt to determine the threshold relationship between flood characteristics and geomorphic changes.

Discussion:
The storm of November 3-5, 1985 caused the resulting flood of November 4-6, 1985. It was the result of Tropical Storm Juan over the Gulf Coast. The rainfall was of a moderate intensity and long duration. The maximum recorded 48-hour precipitation total and recorded rainfall intensity were 310mm (12.2 in.) and 38.3mm/hr (1.5 in./hr) respectively. The average ratio of peak discharge to previous maximum recorded discharge was 2.23 in the South Branch Potomac River and Cheat River basins of West Virginia. The calculated recurrence interval for this flood exceeded 100 years at all of the eleven gages and exceeded 500 years at eight gages. Widespread slope failures, erosion (floodplain stripping and channel widening) and deposition were noted from aerial photographs.

Comparison with floods occurring in 1936 and 1949 indicated that, in this region, debris avalanches in massive sandstones are more likely to occur as a result of a high intensity rainfall, whereas shallow slope failures in terrain overlying shale occur during long duration, moderate intensity rainfall events. The author noted that longer duration, moderate intensity events typically caused more channel and floodplain modification because they tended to occur over a larger spatial scale than high intensity events. Examination of historic floods indicated that events that cause significant geomorphic change occur more often on steep slopes and headwater valleys than in larger valleys.

Unit stream power, a function of discharge, unit weight of water, slope, and width, estimates the ability of streams to erode and transport sediment during storm events. The highest values of unit stream power were found in bedrock canyons because their boundaries were not easily eroded. Erosion occurred downstream of the bedrock canyons when high unit stream power values were combined with wider reaches composed of alluvial bottomland material. Severe erosion of the floodplain downstream of bedrock constrictions was most common in areas where the channel bent to the left or right and flood waters continued straight across the floodplain. Relatively little erosion occurred when the channel and valley were parallel through the reach below a constriction. Lateral variation of hydraulic conditions within a cross section was another factor affecting erosion. Flood flow within a wider channel may concentrate within a small portion of the cross section. In this case, the unit stream power calculated for the entire cross section of the channel would underestimate the rate of expended energy per unit area of bed in the area of the valley where the flow was concentrated.

Results of the evaluation of floods in this region indicated that valleys wider than 200m exhibit increased erosion with increased stream power. Narrower valley channels are less sensitive to unit stream power because the boundaries tend to be less resistant to erosion and the channels tend to run parallel to the valley keeping the central core of flow within the channel. The author concluded that erosion could not be estimated by unit stream power alone, but must include consideration of valley width and slope, channel pattern, spatial variation of roughness elements, and local flow obstructions.

Channelization/Dredging
Criteria: Similar Impacts
Reference: Effects of floodplain and in-channel mining on channel planform

Title: Channel Planform and Land Cover Changes on a Mined Floodplain
Author: Mossa, Joann and Mark McLean
Source: Applied Geography 17(1):43-54
Date: 1997

Location: Amite River in southeastern Louisiana
Land Use: Floodplain was dominated by vegetation(75%) but was reduced to 65% due to increased sand and gravel mining activity.
Watershed Characteristics:
Drainage area 2000 km^2
The basin consists mainly of unconsolidated and semi-consolidated Quaternary sediments. Annual precipitation is about 150 cm (59 in.). The river is coarsely grained.

Objective and Methodology:

The purpose of this study was to investigate the relationship between floodplain and in-channel mining on channel morphology. The goal was to determine if a statistical link exists between floodplain mining and channel change and to provide a quantitative analysis of floodplain variables affecting channel change. Land cover and channel change variables were identified, and examined individually and in combination to explore relationships. The data sources for the study were historical maps of the basin from 1940-1941 and 1980 and 1984. Geographical Information Systems (GIS) was used for areal analysis of the data to determine the degree of channel change and as a mapping tool for other floodplain variables.

Results and Discussion:

The study indicated a moderate correlation between old and new channel position and mining related activities. The changes due to mining typically occurred in response to a large flood. In-channel mining generally caused bed adjustments such as an increase in width to depth ratio. Floodplain mining resulted in changes in channel position. These changes were evident because, at the time of the study, the river no longer ran along the county border as it did in the 1848 map. The distance of the mining pits from the channel influenced the magnitude of channel change due to cut-offs and avulsions. There was a general lag between floodplain changes due to mining and the occurrence of channel change. Channel change was attributed to a number of factors including depth of mining pits, the degree of meander, sediment size, morphology and vegetation, and flow patterns during floods.

Channelization/Dredging
Criteria: Important Concept
Relevance: Effects of channelization on sediment yield and wetland vegetation

Title: Influences of Channelization on Discharge of Suspended Sediment and Wetland Vegetation in Kushiro Marsh, northern Japan
Author: Nakamura, Futoshi, Tadashi Sudo, Satoshi Kameyama, and Mieki Jitsu
Source: Geomorphology, 18:279-289
Date: 1997

Location: Kuchoro River draining into the Kushiro Marsh, in Hokkaido, northern Japan
Land Use: The region is forested in the upper part of the watershed, above 100m in elevation. The mid-basin is cultivated for livestock. Downstream areas of the basin contain wetlands but portions have been gradually changed into pasture.
Watershed Characteristics:
Drainage area 123 km^2
The hillslopes consist of volcanic rocks and gravel sediments. The floodplain consists of volcanic ash and sand and clay deposits. Annual precipitation is 1140 mm (45 in.)

Management:
Channelization occurred between 1965 and 1970 and 1972 to 1980. Ten kilometers of the Kuchoro River were channelized.

Objective and Methodology:

The purpose of this study was to assess the suspended sediment budget in the basin, identify the effects of channelization on sediment yield and channel morphology, and to determine changes in wetland vegetation. The study was conducted from September 6 to October 10, 1995. Two storm events occurred during this time period. Four sites along the river were gaged to record measurements. Suspended sediment load was divided into two components. Wash load was defined as the suspended sediment particles smaller than 0.106 mm. Particles greater than or equal to 0.106 mm were classified as suspended bed material. Channel slope was calculated from a historical topographical map and surveyed during the study. Soil samples were collected from the wetland to assess the organic content. The percentage of wetlands before and after channelization was determined from aerial photographs.

Results and Discussion:

The suspended sediment budget reported that 95% of the total suspended sediment load to the stream came from wash load sediment(fines). Sources of these fine sediments, such as landslides, erosion of agricultural land and channel banks, and degradations of small ditch networks, were cited. The greatest amount of sediment was delivered to the stream and wetland during the two storm events during the study period. Twenty-three (23%) percent of the fine sediment was deposited in the channel along the channelized reach. The remaining 77% (1,120 tonnes) entered the wetland. Conversely, 63% of the suspended bed material was deposited into the channel bed along the channelized reach. Sixty tonnes, 34%, of the suspended bed material entered the wetlands.

Degradation was noted upstream of channelization due to increased flow velocity and average slope increase from 0.1% to 0.2%. The length of the channelized reach was reduced from 20km to 10km. Downstream of the channelized reach, two meters of aggradation accumulated on the channel bed. This aggradation resulted in a 50% reduction in the cross sectional area of the channel.

Organic content of the soils in the wetlands were 10% and 60% in the disturbed and undisturbed areas respectively. The large amount of fine sediment entering the wetland altered the soil structure. Original wetland vegetation was replaced by river riparian vegetation as a result of the change in the soil structure. The study suggested that measures be taken to reduce sediment loads to wetlands through 1)replacement of riparian buffer forests along the channel, 2)creation of side ponds to retain sediment, and 3)drainage of water from the main channel to reduce stream velocity.

Logging

Criteria: Important Concept
Relevance: Effects of land-use changes and climatic variations on a watershed

Title: Fluvial Responses to Land-Use Changes and Climatic Variations within the Drury Creek Watershed, Southern Illinois
Author: Orbock-Miller, Suzanne, Dale F. Ritter, R. Craig Kochel, and Jerry R. Miller
Source: Geomorphology, 6:309-329
Date: 1993

Location: Drury Creek watershed, Southwestern Illinois
Land Use: Forest clearing took place in the mid 1800s due to population growth and a demand for timber. From the 1940s to the present, revegetation and soil conservation practices have been implemented.
Watershed Characteristics:
Drainage area 98km^2
Coarse-grained sandstone is locally exposed in headwaters. In most areas, bedrock is overlain by alluvium or up to 15m of loess. The terrain is moderate to steeply sloping.
Management:
Watershed revegetation and soil conservation practices began in the 1940s.

Objective and Methodology:
The purpose of this study was to determine the effects of major land-use changes and minor climatic changes on the Drury Creek watershed. Characterization of alluvial units was performed to determine sedimentation rates. Channel characteristics measured included: bankfull width and depth, hydraulic radius and slope. Cobbles and pebbles were collected from pools, bars, and riffles. Some cobbles were painted to trace their travel length down the channel.

Results and Discussion:
The average sedimentation rate on the floodplain from 1890 to 1988 was estimated to be 2.11 cm/year. The average rate of sedimentation of only the period from 1940-1988 was estimated to be 1.14 cm/year. The difference between the rates was attributed to increased channel incision from a period of high frequency storms in the mid 1940s and reduction of sediment yield after 1940 due to soil conservation practices. These rates were one to two orders of magnitude larger than pre-logging sedimentation rates in other areas of the midwest (ranging from .020-.650 cm/year). The high rate of sedimentation was attributed to rapid land-use changes which weakened the resistance of hillsides to erosion.

Increased channel gradient and width-depth ratios occurred after 1940 as a result of channel incision caused by the large number of storms between 1945-1951 and reduced sediment yields. Rapid downstream variations in the width-depth ratios occurred as the thickness of coarse bedload material decreased.

Climatic change was examined through precipitation records from 1901-1990. These records indicated that annual precipitation increased through 1904, then decreased through 1944. One exception in this decrease was noted during a wet period between 1927-1929. From 1945-1951, a number of high magnitude storms occurred which caused an increase in the annual precipitation totals. A general increase in total precipitation was noted from 1952-1990. Annual streamflow values tended to follow the precipitation trends. The study concluded that minor climatic change, i.e. increased annual precipitation, enhanced channel response to land-use changes.

Agriculture
Criteria: Similar Impact
Relevance: Effects of stream fencing on sediment losses from pastures

Title: Sediment Losses from a Pastured Watershed Before and After Stream Fencing
Author: Owens, L.B., W.M. Edwards, and R.W. Van Keuren
Source: Journal of Soil and Water Conservation, 51(1):90-94
Date: 1996

Location: North Appalachian Experimental Watershed near Coshocton, Ohio
Land Use: 92% Pasture
Watershed Characteristics:
Drainage area 28.2 hectares (69.7 acres)
Slopes of the pastured areas ranged from 2% to 35% and averaged 17%. A clay layer outcrop was located midway down the slopes on each side of the watershed. Well drained and moderately well-drained silt loams lay above and below the clay layer respectively. Perennial grasses made up most of the pastured area.

Management:

A herd of beef cows grazed on the entire pastured area (26.0 hectares) from 1980 to 1987. No fertilizer was applied to the watershed. In 1987, an electric fence kept cattle out of approximately 4.6 hectares of the same area. The cattle grazed from 1987 to 1993. The herd size remained constant.

Objective and Methodology:

The purpose of this study was to examine the difference in soil loss from an unfertilized pasture under continuous grazing with and without stream fencing. Storm runoff and precipitation were measured throughout the study.

Results and Discussion:

The average sediment concentration in the storm flow was reduced by 60% after fencing. This corresponded to an average annual soil loss decrease of 40% (2.5Mg/ha to 1.4 Mg/ha) after installation of the stream fencing. This occurred despite a 30% increase in average annual storm flow. The decrease in soil loss was attributed to decreased stream bank cutting by livestock. Less than 1% (3 out of 413) of the storm events during the study period accounted for 27% of the total soil loss. These rare events were usually preceded by intense precipitation and caused a high amount of soil loss.

Agriculture
Criteria: Similar Impact
Relevance: Effects of agriculture land use on erosion and sediment yield

Title: Pre- and Post-Colonial Sediment Sources and Storage in the Lower Neuse Basin, North Carolina
Author: Phillips, Jonathon D.
Source: Physical Geography, 14(3):272-284
Date: 1993

Location: Lower Neuse River basin on the North Carolina Coastal Plain
Land Use: The watershed was cleared in the early 1700s by European settlers. Agricultural use is the dominant land use in this basin.

Watershed Characteristics:
Drainage area 16,000 km^2
The soils in the study area are loamy sand and loamy fine sand. The climate in this region is humid subtropical. Annual precipitation ranges from 100 cm (39 in.) to 130 cm (51 in.). Most of the region is less than seven meters above sea level. A control watershed was chosen in the Croatan National Forest at Flanner's Beach. This site had not been disturbed by logging or agricultural land clearing at the time of the study.

Objective and Methodology:
The purpose of this study was to compare the sediment dynamics of the Neuse River basin to those that existed before colonization. Upland erosion rates were estimated from soil profile truncation. Sediment yields were measured using suspended sediment data from USGS gaging stations in the North Carolina Coastal Plain. The sources of deposition on the floodplain were identified. Storage of post-colonial sediment along the Neuse basin was assessed.

Results and Discussion:
The rate of upland erosion in the contemporary undisturbed forest was negligible and taken to be zero. The rate of upland erosion in the Neuse River basin in post-colonial times was estimated to be about 10 tonnes/hectare/year.

Suspended sediment was examined in basins with increasing levels of agricultural activity. Basins which were 100% forested yielded only about 0.02 tonnes/hectare of suspended sediment. The Trent River basin, with a forest cover of 77%, yielded 0.05 tonnes/hectare annually. In contrast, five Coastal Plain basins with agricultural land covering 20-43% of the watersheds averaged 0.11 to 0.17 tonnes/hectare of suspended sediment per year.

Sediment delivery to lower reaches of the watershed was low in pre-colonial times with only an upper-basin Piedmont contribution. After colonization, the delivery was still low, however, Coastal Plain derived sediment was the major source of sediment.

Storage of sediment in the floodplain was assumed to be minimal in pre-colonial times due to the fact that the upland erosion rates were about the same as the suspended sediment transport rates. In post-colonial times, erosion rates were much higher than suspended sediment transport rates. Therefore, the amount of sediment stored in the floodplain increased greatly since land clearing for agriculture purposes. The study concluded that the impacts of human activity in flatland areas was as substantial as in steeper areas.

Agriculture
Criteria: Similar Impact; Important Concept
Relevance: Relates to the issue of whether changes within a watershed are a result of climatic variability or anthropogenic changes. Indicates that conservation practices may improve watershed hydrologic and geomorphic conditions.

Title: Hydrological Impacts of Changing Land Management Practices in a Moderate-Sized Agricultural Catchment
Author: Potter, K.W.
Source: Water Resources Research, 27(5):845-855
Date: May, 1991

Location: East Branch of the Pecatonica River, Wisconsin
Land Use: Agricultural
Watershed Characteristics: Drainage area of 221 mi^2, steep slopes, high percentage of precipitation, highly susceptible to erosion
Management: Conservation tillage in Iowa County in 1984 and 1985

Objective and Methodology:

Due to decreasing trends in annual flood series, the main objective of this study was to assess the impact of soil erosion management practices on flood reduction. The study was conducted to explain the causes of this trend which may be due to climatic variability or changes in agricultural practices. There was little available data on land use and management practices. Since little land use and management practice information were available, hydrologic trends due to these factors had to be based on information from hydrological changes and from possible climatic variability. Flood events organized into two flood seasons were observed: winter/spring and summer/fall. For the winter/spring events, base flow increase due to each event was also estimated and evaluated for temporal trend. Climatic variables which could cause hydrologic trends were tested to assess the influence of climatic variability.

Results and Discussion:

Analyzed climatic data did not explain climatic variability causes to hydrological changes in the summer/fall floods. Winter/spring flood volumes showed a decreasing trend while there was an increase in base flow over time. The increase in base flow was computed as a result of the annual snowmelt event. The decreasing trend in 3-day flood volume was offset by the increasing trend in base flow. Variations in climate could not be explained for the trends in base flow and flood volumes for the winter/spring floods.

There was no significant correlation in these trends to climatic changes which led to believe that the trends were caused by agricultural land use and practice. There was a decrease in total area in agricultural land since 1950, but since 1955 there has been little change in acreage of particular crops planted. Therefore, there was little land use change in the time of study. There were increases in the use of row crops which may have caused the changes. Since the late 1930s, farmers have participated in conservation programs, but whether specific practices have been implemented or not is not documented. Conservation tillage practices could explain the decrease in winter/spring flood volumes and the increase in base flow because of their ability to reduce runoff and erosion. Snowmelt runoff is most likely reduced by these practices as well by increasing soil moisture and being more effective in trapping snow. Since base flow volumes increased due to snow melt, conservation tillage was probably the cause.

Channelization/Dredging
Criteria: Similar Impact
Relevance: Effects of channelization of flooding

Title: Channelization Effects on Obion River Flooding, Western Tennessee
Author: Shankman, David and Scott A. Samson
Source: Water Resources Bulletin, 27(2):247-254
Date: 1991

Location: Obion-Forked Deer River, Western Tennessee. The mouth of the Obion River runs into the Mississippi River.
Land Use: Lowlands have remained forested but much of the watershed has been cultivated for agricultural use.
Watershed Characteristics:
Drainage area 11,650 km^2
The floodplain occupies approximately 26% of the watershed. About 35% of the total number of streams in the watershed were channelized in the 1960s. The Obion River is a low-gradient Coastal Plain stream. The dominant soil type is silt loam. The climate is humid subtropical. Mean monthly temperatures range from 5°C to 28°C. The wet season occurs in late winter and early spring.

Objective and Methodology:

Three stream gages along the Obion River and one gage along the Mississippi River at the mouth of the Obion were used for data collection. Streamflow data was collected at the gages and used to calculate monthly flood frequency, number of non-flood days per year, and maximum annual streamflow.

Results and Discussion:

Flood frequency on the upper Obion decreased significantly (24%, 59%, and 92% at the three gages)after channelization. The decrease in floods downstream was not significant due to backwater flooding from the Mississippi River and sediment deposition which reduced the cross sectional area of the channel. Downcutting of the channel banks caused them to erode and retreat up to one meter per year. Mean and maximum annual streamflow increased slightly after channelization. The annual maximum water level remained the same after channelization. Thus, the area of the floodplain which typically became submerged each year remained constant.

Channelization/Dredging

Criteria: Important Concept
Relevance: Effects of stream channelization on lowland vegetation

Title: Stream Channelization and Changing Vegetation Patterns in the U.S. Coastal Plain
Author: Shankman, David
Source: The Geographical Review,86(2):216-232
Date: April, 1996

Location: U.S. Gulf Coastal Plain, major rivers in western Tennessee and northwestern Mississippi
Land Use: Extensive land clearing occurred in the late 1800s. Today much of this land is used for agriculture.

Watershed Characteristics:
These watersheds contain low-gradient streams covering highly erodible loess soils. Floodplains typically cover 10% of the watersheds. Most streams flood each year during the winter and spring, submerging the floodplains for up to several weeks.

Management:
Much of this region was deforested in the late 1800s for agricultural purposes. Most of the major streams were channelized for the first time in the 1920s or 1930s. Channelization has been performed, by the Army Corps of Engineers and the Soil Conservation Service, since the 1950s.

Objective and Methodology:

The purpose of this study was to examine the effects of channelization on low-lying vegetation patterns in the U.S. Coastal Plain. Changes in vegetation as a result of channelization were studied based on channel morphology and historical characteristics of bottomland species.

Results and Discussion:

Channelization reduced flooding on the upper reaches of streams. This limited the distribution of bottomland species, such as water tupelo, black willow, cypress, silver maple, water elm, and river birch, to the narrowed region of the floodplain. Drier species, such as chestnut oak, water oak, winged elm, and red maple, migrated to lower-lying areas but only to areas where flood occurrences were rare. Channelization increased flooding downstream due to channel straightening and increased channel velocity. The study suggested that downstream flooding would prevent regeneration of some bottomland species by submerging and killing seedlings.

Increased water velocity following channelization caused stream incision. This incision led to the creation of gullies which drained shallow impoundments adjacent to the streams. Water in these impoundments supported plant communities dominated by bald cypress and water tupelo. Species that are tolerant to seasonal flooding, such as oak, birch, and elm, as opposed to continuous flooding migrated to this area.

Channel straightening impeded the formation of point bars and the filling in of oxbow lakes. Unique plant communities supported by these formations, such as black willow, cottonwood, and silver maple, were eliminated. The study concluded that channelization directly or indirectly caused the loss of habitat diversity in adjacent floodplains.

Channelization/Dredging

Criteria: Similar Impact
Relevance: Effect of channelization on sediment load

Title: The Discharge of Sediment in Channelized Alluvial Streams
Author: Simon, Andrew
Source: Water Resources Bulletin, 25(6):1177-1188
Date: 1989

Location: West Tennessee, bounded by the Mississippi River on the west and the Tennessee River divide on the east.
Land Use: Mainly agricultural and forest land
Watershed Characteristics:
West Tennessee is about 10,600 mi^2 in area. The major rivers of the region are the Obion, Forked Deer, Hatchie, and Wolf rivers. All the rivers drain to the Mississippi. These channels represent stages in channel evolution. The river beds consist of medium-sand and silt. Straightening and dredging of the channels occurred periodically starting around 1900. The most recent changes included shortening channels by about 44%, increasing gradients up to 600%, and lowering channel beds by as much as 17 feet.

Objective and Methodology:

The purpose of this study was to determine trends of sediment discharge in streams at different evolution stages. The Hatchie was considered to be a control stream since it did not undergo channelization. The three areas of study were suspended sediment transport, channel bed material, and morphologic changes. Fourteen gages along these rivers were used to collect suspended sediment data. Streamflow measurements were made at these gages as well. Bed material discharge was estimated by relating channel bed material transport to mean flow velocity.

Results and Discussion:

Average suspended sediment loads ranged from 163 tons/yr/mi^2 to 2490 tons/yr/mi^2. The lowest suspended sediment load occurred during early stages (pre-channelization) of stream evolution as a result of sheet erosion and gullying. The greatest yields of suspended sediment occurred in reaches at the threshold stage (prior to aggradation). Higher yields resulted from straightened channels that did not dissipate energy in the form of friction and were able to transport more sediment.

Channel bed material transport was calculated for periods where stream velocity data existed. Bed material discharge values ranged from 1.0 to 1,530 tons/day for reaches in the initial (pre-channelization)and degradation (post-channelization) stages respectively. Bed material yield increased steadily through the degradation stage (when the banks were the most unstable). Yield then dropped off sharply during the aggradation and restabilization stages as woody vegetation was reintroduced to the channel banks increasing channel roughness.

Eroded bed material accounted for approximately 24% of the total sediment eroded. These sediments were coarse grained and did not leave the system but took part in channel recovery downstream. The fine grained material that was suspended sediment was almost completely carried out of the system into the Mississippi River. This material accounted for almost 400 million cubic feet of sediment entering the Mississippi in 20 years.

Channelization/Dredging

Criteria: Important concept
Relevance: Effects of channelization on gradation processes and channel evolution

Title: Gradation Processes and Channel Evolution in Modified West Tennessee Streams: Process Response, and Form
Author: Simon, A.
Source: USGS Professional Paper 1470:1-63
Date: 1994

Location: Gulf Coastal Plain Province, Western Tennessee
Land Use: Lowlands have remained forested but much of the watershed has been cultivated for agricultural use. Large tracts of land were cleared about 1910. This led to erosion of the uplands. The time period covered by this study was from the late 1950s to 1983.
Watershed Characteristics:
Area 27,500 km
The area containing the 13 streams studied lies in West Tennessee bounded by the Mississippi River on the west and the Tennessee River divide on the east. All streams drain into the Mississippi River from the Obion, Forked Deer, and Hatchie River basins. Most of the streams flow through deposits of loess. The channels were sinuous.

Management:
Following land clearing in the early 1900s, the channels became loaded with sediment and were subject to flooding. In 1926, most of the channels, with the exception of the main stem of the Hatchie, were dredged and straightened to increase drainage. This caused enlargement of channels due to increased velocity. Trees accumulated in the stream due to bank failure. For this reason, channelization was performed periodically to keep channels free of debris.

Objective and Methodology:

The purpose of this study was to determine rates of gradation processes of the 13 streams in the above mentioned basins, establish relationships between gradation processes and channel response during stages of bank-slope development, and to develop a conceptual model of channel evolution from these relationships.

Historical (pre-modified) data were obtained from USGS dredging plans, gage data, and plotted profiles. Current data were obtained from a field study conducted in 1983 and 1984. Channel geometry data, such as bed elevation, channel gradient, channel width, bank height, and type of geomorphic surface, were collected in the current field study to measure morphological change as a result of channelization. Channel alluvium characteristics were studied from 244 samples of bank material, 100 samples of bed material, and 22 samples of recent deposits. Channel adjustments, such as incision, degradation and bank instability, and downstream aggradation, were observed.

Results and Discussion:

Gradation processes and channel adjustments were described as a function of the magnitude of disturbance (channelization) on a channel and the location of the adjusting reach. Aggradation and degradation were described by an exponential decay function of distance away from the area of maximum disturbance. In Tennessee streams, degradation was caused by increases in channel gradient and capacity downstream and removal of riparian vegetation. These changes resulted in an increase in stream power which transported more bed material downstream. Increased degradation, upstream of the point of disturbance, caused sediment loads that the stream could not support. As a result, aggradation and the recovery of the bed level began.

Channel width adjustment and bank-slope development caused by channelization were a result of channel bed changes. As the bank profile became steeper from degradation and downcutting, the bank was destabilized. Channel width adjustments and bank failures did not occur at the same time as degradation. Rather, a lag time existed during which downcutting of the banks occurred to induce bank failure. Channel widening rates ranged from 1.1 m/year to 2.4 m/year at two sites at which the data necessary for rate estimation was available.

Bank-slope development was observed and categorized into six stages according to 1)location in the stream network, 2)dominant process on the channel bed, and 3)state of channel widening. These stages were as follows:

Evolution Stage	Location in stream network	Dominant process	State of channel widening
1)Premodified	Upstream reaches	Sediment transport and mild aggradation	None
2)Constructed	Where applicable	Dredging	Caused by man
3)Degradation	Upstream of area of maximum disturbance	Degradation	None
4)Threshold	Upstream of area of maximum disturbance	Degradation	Active
5)Aggradation	Upstream of area of maximum disturbance	Secondary aggradation	Active
6)Restabilization	Downstream of area of maximum disturbance	Aggradation	None

The study suggested that extrapolation of this model to other areas of the Mississippi River and the Central United States was appropriate. The concept of this model could be applied to a broader geographical region.

Logging
Criteria: Includes New England Example
Relevance: Provides a contradictory view that clear-cutting produces significant changes in nutrient runoff to streams.

Title: Effects of Timber Harvesting and Relating Management Practices on Water Quality in Forested Watersheds
Author: Sopper, W.E.
Source: Journal of Environmental Quality, 4(1):24-29
Date: 1975

Location: New Hampshire, North Carolina, W. Virginia, Pennsylvania, and Oregon
Land Use: Forested

Objective and Methodology:

To identify the effects of forest management practices on water quantity and quality, literature containing the results of several studies were reviewed by the author. Studies researching the effects of timber harvesting on water temperature, water turbidity, and nutrient water quality were examined.

Results and Discussion:

In a watershed in West Virginia which was logged with a careful plan and maintained roads showed only minor increases in turbidity compared to commercial clear-cutting with no road maintenance.

Forest cover removal has shown increases in water temperature. In watersheds in North Carolina, West Virginia, Pennsylvania, New Hampshire, and Oregon, water temperatures were increased (4-8E C) by clear-cutting. Water temperature increases can be decreased by allowing a buffer zone along the stream bank (Swift and Messer, 1971, Kochenderfer and Aubertin, 1974, Lynch et al., 1974, Pierce et al., 1970, Levno and Rothacher, 1967, and Brown and Krygier, 1970).

In Hubbard Brook, New Hampshire, an extreme case of increased nutrient runoff due to clear-cutting was documented by Likens et al. (1970). This area was spread with herbicides for three consecutive summers to prevent regrowth and was left undisturbed without roads and trails. Nitrification and decomposition of organic matter was accelerated because of higher nutrient availability from the de-vegetation. Nutrient leaching to streams increased because of the decline in living vegetation which could absorb the nutrients and nitrate concentrations in the streams increased. In the White Mountains of New Hampshire, Pierce et al., (1972) saw increases in nitrate concentrations in streams draining from clear cut areas. Another study at Hubbard Brook, NH revealed that patterns of partial clear-cutting such as strip-cutting can have less drastic nutrient losses from forested watersheds than traditional clear-cutting (Hornbeck et al., 1974).

The Hubbard Brook watershed studies in NH had contrasting results of nutrient loss compared to other studies in the United States. In Fernow watersheds in West Virginia, nutrient concentrations in forested and clear-cut watersheds were similar (Aubertin and Patric, 1972). It was concluded that the clear-cutting in Hubbard Brook watershed had more drastic differences in concentrations because it did not experience the re-vegetation that occurred in the Fernow watersheds and that there were was no tree harvest. In Pennsylvania, another clear-cutting project showed little differences in nutrient concentrations before and after clear-cutting because the clear-cutting was partial (Lynch et al., 1973). When logging and burning of forests occurred in western Montana, there was a rapid increase in nutrient runoff in the first year with continued increases for four years. Another clear-cutting and burn procedure in the H.J. Andrews Experimental Forest, Western Oregon caused moderate losses of phosphorus and nitrogen (Fredriksen, 1971; and Fredriksen et al., 1974).

Within 4 years, the nitrate concentrations were at the levels prior to the clear-cutting because of rapid re-vegetation.

According to the author, clear-cutting results in negligible losses of nutrients except for the Hubbard Brook study in NH where herbicides were used to prevent re-vegetation. The author pointed out that all other studies reviewed showed nutrient losses drastically lower than Hubbard Brook.

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Swift, L.W., Jr. and J.B. Messer, 1971, "Forest Cuttings Raise Temperatures of Small Streams in the Southern Appalachians", J. Soil Water Conserv., 26:111-116.

Logging

Criteria: Similar Impact
Relevance: Ability of streamflow characteristics in a watershed to return to equilibrium conditions after logging.

Title: Problems in Determining the Return of a Watershed to Pretreatment Conditions: Techniques Applied to a Study at Caspar Creek, California
Author: Thomas, Robert B.
Source: Water Resources Research, 26(9): 2079-2087
Date: September 1990

Location: North and South Forks of Caspar Creek, Jackson Demonstration Forest (approx. 11 km SE of Ft. Bragg and 7 km. from the Pacific Ocean).
Land Use: Logged in late 1800's, second growth regeneration.
Watershed Characteristics:

<u>North Fork Watershed</u> (Control)
483 ha
Elev. 37 to 320 m
35 % with slopes less than 30 %
7 % steeper than 70 %
Note: forest left intact

<u>South Fork Watershed</u>
424 ha
Elev. 37 to 320 m
35 % with slopes less than 30 %
1 % steeper than 70 %
Note: 67 % of forest volume removed

Topography ranges from broad, rounded ridge tops to steep inner gorges. Climate is Mediterranean with mild summers (10E to 25E C) and wet winters with avg. rainfall of 1200 mm (47 inches) per year. Soils are predominately derived from sandstone, and are well drained with high hydraulic conductivities.

Management: Both watersheds were clear-cut, logged, and burned in the late 1800's. Second growth stands of redwood and Douglas fir exist on the site now with some western hemlock and grand fir. During the study period, 67-percent of the forest volume of the South Fork Watershed was removed.

Objective and Methodology:

The objective of this study was to determine whether a previously logged watershed (the South Fork Watershed) had recovered enough to be used as the control watershed for future study. The author looked at data collected from previous studies which included three storm based discharge characteristics (peak discharge, quick flow, and total storm flow), daily flows, and concentration of suspended solids. The author evaluated the data using a variety of statistical methods as well as a summary evaluation of methodologies of previous studies. The author divided the work performed at Caspar Creek into six time periods; 1) calibration (4 years); 2) road building (3 years); 3) logging (4 years); 4) recovery period 1 (1 year); 5) recovery period 2 (3 years); and 6) recovery period 3 (3 years).

Results and Discussion:

In all characteristics evaluated, the author found biases caused by data collection methods or statistical analysis. The author found no statistically significant links between peak storm discharge and the logged watershed although the median increased. One explanation is too few storm events to evaluate. The author found statistically significant changes in total storm discharge but not in quick flow, implying that logging can increase base flows. These increases lasted approximately 7 years after the commencement of road building until the first recovery period. The author found that daily flow was the characteristic most sensitive to logging and that these had not fully recovered by recovery period 3 (11 years after the commencement of logging).

Sediment data collected at the Caspar Creek watershed was variable and inconsistent. The author found the general trend to be high sediment losses in recovery period 1 (the first year after cutting) and levels approaching prelogging conditions by recovery periods 1 and 2.

Urbanization

Criteria: Important Concept
Relevance: Management of stormwater runoff quality

Title: Modeling and Management of Urban Stormwater Runoff Quality: A Review
Author: Tsihrintzis, Vassilios A. and Rizwan Hamid
Source: Water Resources Management, 11:137-164
Data: 1997

Objective:

This paper was a review of recent regulations and studies regarding urban runoff control in the United States. It discussed nonpoint source (NPS) pollution, reviewed current hydrologic and water quality models, presented case studies of watershed modeling and management, explained Best Management Practices (BMPs), and proposed future areas of research.

Discussion:

The quantity and quality of urban runoff was characterized as a function of the following: rainfall patterns, volume, intensity, and number of dry days preceding the storm; traffic volume; land use; regional geography and geology; maintenance practices; drainage system configuration.

Processes which led to stormwater quality problems were described and included atmospheric scrubbing, scour and erosion of exposed surfaces and pollutants in the soil, surface washoff. Pollution transport, transformation, and deposition also contributed to the urban runoff.

Pollutants found in stormwater runoff included suspended solids, heavy metals, chlorides, oils, grease, and hydrocarbons. These pollutants caused problems with water quality ranging from, accumulation of heavy metals and toxics in river beds to the death of fish due to oxygen-depleted conditions in the stream.

The Nationwide Urban Runoff Program (NURP) was reviewed which was as study conducted by EPA to examine the stormwater pollution problem. The goal was to aid decision makers by identifying pollutants (listed above) and characterizing urban runoff. The Federal Highway Administration Study, conducted in 1981, identified roadway contaminants and their sources, road design and maintenance practices affecting the quality of highway runoff. Data comparisons of biochemical oxygen demand (BOD) and total suspended solids (TSS) indicated that loads from highway runoff were about equal to loads from storm sewer discharges.

Mathematical models used to assess NPS pollution were described. The most important and widely used models included Aerial, Nonpoint Source Watershed Environmental Response Simulation (ANSWERS), Agricultural Nonpoint Source (AGNPS), Hydrologic Simulation Program-FORTRAN (HSPF), Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS), Simulator for Water Resources in Rural Basins (SWRRB), Pesticide Root Zone Model (PRZM), Agricultural Runoff Model (ARM), and Agricultural Chemical Transport Model (ACTMO). Some of the most popular models used specifically for stormwater modeling included Storm Water Management(SWMM), and Storage Treatment Overflow Runoff Model (STORM).

Best Management Practices (BMPs) were discussed and evaluated. The list of well known BMPs included infiltration trenches, dry wells, infiltration basins, grass swales, porous pavements, extended detention dry ponds, artificial marshes, wet detention basins, recharge basins, sand filters, and oil/grit separators. BMPs which consistently performed a moderate to high level of removal of pollutants and particulates were wet ponds, artificial marshes, sand filters, and infiltration trenches. Infiltration basins, porous pavement, grass filters, smaller wetlands, extended detention dry ponds, and oil/grit separators were not considered to reliably reduce pollution.

Urbanization, Channelization/Dredging
Criteria: Important Concept
Relevance: Sources of sediment in streams

Title: Sources of Sediment
Author: Waters, Thomas F.
Source: *Sediment in Streams: Sources, Biological Effects, and Control*, American Fisheries Society, Bethesda, MD :36-51
Date: 1995

Objective:

This excerpt identifies and discusses sources of sediment in streams. The areas of discussion summarized are sand and gravel extraction, urban development, and streambank erosion.

Discussion:

The two major forms of sand and gravel extraction are streambed dredging and floodplain excavation. Physical effects of sand and gravel mining include changed channel morphology and upstream erosion due to increased stream velocity. Fine particle deposition and high turbidity due to suspended sediment may result from these effects. Studies from six states noted reduced photosynthesis and decrease in the biomass and number of fish species in streams that had been dredged. Streams were slow to recover from the effects of sand and gravel excavation. In one cited study, the Big Rib River in Wisconsin exhibited only the early stages of recovery 20 years after excavation ended (Kanehl and Lyons, 1992).

Urbanization was described as a major source of sediment, causing significantly higher sediment loads to streams than rural land use. In a study of the Occoquan River, just southwest of Washington D.C., suspended sediment was the single greatest pollutant found in a water supply reservoir at the river mouth (Randall et al., 1978). In a 1962-1974 study, suspended sediment yield from urban areas of the Anacostia River, north of Washington D.C., was up to 6 and 120 times the yield from cultivated and forested areas respectively. Control measures, such as installation of settling basins, temporary vegetation during construction, and earlier installation of final vegetative cover, decreased suspended sediment yield by 60%-80% (York and Herb, 1978).

Streambank erosion, described as a natural process in streams, is magnified by urbanization, agricultural use, and channelization. Urbanization causes increased streamflow which encourages streambank erosion. A study of 20 streams in Michigan's Lower Peninsula showed that streams in forested watersheds exhibited stable flows and less sediment than streams in watersheds developed for agricultural use (Wilson, 1964). Channelization steepened channel gradients and increased flow velocities which quickened streambank erosion (Harvey et al., 1985).

Note: References cited can be found in the source text.

Channelization/Dredging
Criteria: Similar Impact
Relevance: Effects of channelization on flow and sedimentation

Title: Environmental Impacts of Channelization on the River Main, County Antrim, Northern Ireland
Author: Wilcock, David N. and Charles I. Essery
Source: Journal of Environmental Management, 32:127-143
Date: 1991

Location: River Main basin, Northern Ireland
Land Use: Mainly agricultural
Watershed Characteristics:
Drainage area 205 km^2
Soil in the flood plain are mainly alluvial and peat deposits above glacial gravel.
Management:
The channel was widened, deepened, and straightened over 26 km between the mid-1970s and 1987. Channelization was performed to increase agricultural drainage and reduce flooding on 4300 hectares of agricultural land.

Objective and Methodology:

The purpose of this study was to quantify the effects of channelization on hydrology, flow characteristics, and suspended sediment loads on the River Main. A before and after detailed survey of the basin was performed. Precipitation, groundwater storage, and streamflow were measured at five locations every two weeks throughout the study. Suspended sediment was measured at one gage. The concentration of suspended sediment was taken as the mean of samples from different stream depths.

Results and Discussion:

Streamflow in the River Main increased by almost 5%. Streamflow on the tributaries decreased at all but one gage. Low flows were higher after channelization at all but one gage.

Water was taken out of groundwater storage as a result of channelization. Storage of water and nutrients in low-lying wetlands was almost completely eliminated due to channelization. Draw down of the groundwater level did not occur significantly beyond a distance of 35m from the river. Thus, only 37% of the agricultural area estimated to receive a direct drainage benefit by channelization actually received a drainage benefit.

Channelization shortened the river by 23%. Channel slope and roughness were increased by 30% and 50% respectively. The magnitude of flow velocity exceeded 95% of the time in the river increased three times after channelization while the magnitude of flow velocity exceeded 10% of the time increased a little over two times. Higher streamflow velocities did not increase as much as low streamflow velocities after channelization. Natural pool and riffle sequences along the river were eliminated as a result of channelization. Pool and riffle elimination, along with associated increased velocity, were considered to have impaired the habitat quality of the river system for salmonids by hindering upstream migration.

Suspended sediment loads increased due to the excavation of unconsolidated bed and channel wall sediment. Pre-channelization median concentrations of suspended sediment was 7.8 mg/l. Post-channelization median concentrations of suspended sediment was 54.76 mg/l. Flood concentrations of suspended sediments increased from about 100 mg/l to as high as 546 mg/l.

Urbanization
Criteria: Similar Impact; Important Concept
Relevance: A description of the upset of equilibrium in streams and geomorphic change due to urbanization.

Title: A Cycle of Sedimentation and Erosion in Urban River Channels
Author: Wolman, M.G.
Source: Geografiska Annaler, 49A:385-395
Date: 1967

Location: Piedmont of Maryland
Land Use: Agriculture into urban
Watershed Characteristics:
Drainage area of 0.0025 to 303 mi^2

Objective and Methodology:

This study evaluated historical evidence and measurements to observe the geomorphic change in a Piedmont region of Maryland in relation to land use change which upset the river's equilibrium. The purpose of this paper was to review, add to, and evaluate evidence for successive stages in the urbanization/geomorphic change cycle.

Results and Discussion:

When urbanization occurs within a watershed, the transport of sediment and water are altered and the current equilibrium of the channel system is disturbed which may result in the development of new equilibrium conditions or the persistence of disequilibrium.

The cycle of sediment yields and geomorphic change with the urbanization cycles is as follows:

1. wholly forested: sediment yield of $<$ 100 tons/mi^2
1. agricultural: sediment yield of 800 tons/mi^2; accumulation of sediment in channels
1. just before construction: sediment yield of approximately 200-300 tons/mi^2
1. construction: sediment yield of several thousand tons/mi^2 (up to $>$ 100,000 tons/mi^2 in very small areas entirely under construction); coarse grain sediment aggradation, channel constriction, bank erosion
1. post-construction: sediment yield as low or lower than pre-farming values of approximately 50 tons/mi^2 ; runoff increases, rapid erosion with no deposition, hence channel widening and abnormal flood plain formation

Suspended sediment concentrations in urban rivers ranged from 97 to 226 ppm during non-storm periods and as high as approximately 800 ppm in the discharge of a 1.5 year flood.

In urban channels, little or no buildup of point bars takes place. Deposits within channel formations which formed during the construction era can be removed over a number of years once the channel is urbanized. When the widths of channels in Pennsylvania and Maryland were compared, urban channels were much wider than "natural" or agricultural channels. Photographs comparing post flooding geomorphic features to urban channel features were very similar such as abrupt channel widening. The excessive erosion after watershed development can be attributed to increased magnitudes of peak flows and the decrease of sediment availability.

Urbanization

Criteria: Similar Impact

Relevance: Land use changes effects on sediment yields and fluvial geomorphology

Title: Effects of Construction on Fluvial Sediment, Urban and Suburban Areas of Maryland
Authors: Wolman, M. Gordon and Asher P. Schick
Source: Water Resources Research, 3(2):451-464
Date: Second Quarter 1967

Location: Baltimore, Maryland and Washington, D.C.
Land Use: Urban and Suburban
Watershed Characteristics: Annual precipitation 1100 mm (42 inches), Slope 1-10% with some areas up to 20%,

Objective and Methodology:

The sediment yield for ten streams where construction activities were minimal were researched and tabulated to determine background sediment yield. Nine of the streams represent rural regions in Maryland and the other was a wooded drainage area in Kentucky. Sediment yields were researched and tabulated for 12 drainage areas in the Baltimore and D.C. area which were under construction. In addition, 35 road cuts in Maryland were measured to analyze the sediment yield caused by rill erosion from a 15 foot wide strip across the slope. To determine exposure time during construction 100 randomly selected building permits were analyzed. Social and economic impacts of sediment derived from construction activities were studied utilizing : 1) questionnaires mailed to builders; 2) reports of the water Pollution Control Commission; and 3) estimates of costs associated with sediment removal, accumulation, or damage.

Results and Discussion:

The rural and wooded drainage areas measured had sediment yields of 15 to 913 tons/mi^2/year with and average of 200 to 500 tons/mi^2/year. These drainage areas ranged from 0.85 to 817 square miles. Since most of the farms in this region are fallow and regenerating to brush the sediment yield from such areas is perhaps at the all time low in recent history. Relatively small drainage areas (0.0025 square miles) under construction development had sediment yields as high as 140,000 tons/mi^2/year where larger areas of 72.8 square miles had sediment yields of 1060 tons/mi^2/year. In the smaller drainage area construction acreage is actually a large percentage of the drainage area whereas in the larger drainage areas construction acreage is relatively small. Thus, dilution is a factor in the declining yields for larger drainage areas. Regardless, the author contends that the quantity of sediment from areas undergoing construction is 2 to 200 times that of areas in a rural or wooded condition.

The road cuts in the Baltimore area consistently showed that the volume of material in the fans at the base of the slope were always greater than the estimated loss from sheet and rill erosion on the road cut slope. This indicates that sheet and surface erosion are also contributing to the total sediment yield at the base of the slope. A total sediment yield from a two lane highway construction project represents 3000 tons per linear mile.

The review of the building permit records revealed that construction sites remain exposed for longer periods than previously thought. Approximately 50 percent of the construction sites remained exposed for eight months and 60 percent for nine months. The builders questionnaire revealed that median completion time was ten months. The sites were almost always exposed during the heavy summer rains.

Logging

Criteria: Similar Impact
Relevance: Logging and road building effects on streamflow, storm volumes, quick flow volumes, and peak flows.

Title: Logging Effects on Streamflow: Storm Runoff at Caspar Creek in Northwestern California
Author: Wright, Kenneth, Karen Sendek, Raymond Rice, and Robert B. Thomas
Source: Water Resources Research, 26(7):1657-1667
Date: July 1990

Location: North and South Forks of Caspar Creek, Jackson Demonstration Forest (approx. 11 km SE of Ft. Bragg and 7 km. from the Pacific Ocean).
Land Use: Forested: Logged in late 1800's, second growth regeneration.
Watershed Characteristics:

North Fork Watershed (Control)	South Fork Watershed
483 ha	424 ha
Elev. 37 to 320 m	Elev. 37 to 320 m
35 % with slopes less than 30 %	35 % with slopes less than 30 %
7 % steeper than 70 %	1 % steeper than 70 %

Topography ranges from broad, rounded ridge tops to steep inner gorges. Climate is Mediterranean with mild summers (10E to 25E C) and wet winters with avg. rainfall of 1200 mm (47 inches) per year. Soils are predominately derived from sandstone, and are well drained with high hydraulic conductivities.

Management: Both watersheds were clear-cut, logged, and burned in the late 1800's. Second growth stands of redwood and Douglas fir exist on the site now with some western hemlock and grand fir.

Objective and Methodology:

The objective of the study was to determine the effects of logging, road construction, and soil compaction from heavy equipment use on storm volumes, quick flows, and peak flows. Stream gauging stations were placed on both forks in 1962 along with four rain gauges to measure precipitation. Both watersheds were monitored in undisturbed hydrologic conditions for four years. Road construction in the South Fork watershed was begun in 1967. Logging effects were monitored 9 years for flow analysis and 14 years for lag time analysis.

Results and Discussion:

By the end of the study, roads, landings, and skid trails occupied 15-percent of the watershed. Soils beneath these areas were considered to be heavily compacted. The study found no change in stream flow regime due to road construction, but suggest that the roads were close to the streams and therefore intercepted water late in the flow regime. The study found that the effect of compaction and logging was the increase of small storm (less than 1209 m^3/s) runoff values. Logging practices contributed to a 132-percent increase in stream flow volumes, a 170-percent increase in quick flow volumes, and a 111-percent increase in peak flow volumes during small storm events. In some small storm events volume increased as much as 290-percent and peak flows as much as 240-percent. However, no significant effect could be found during large storm events. Suggested reasons for the volume increases included reduced evapotranspiration, and reduced interception from tree removal and soil compaction.

Channelization/Dredging
Criteria: Important Concept
Relevance: Effects of channelization on flood wave magnitude

Title: Changes in the Magnitude and Transformation of Flood Waves Subsequent to the Channelizaiton of the Raba River, Polish Carpathians
Author: Wyzga, Bartlomiej
Source: Earth Surface Processes and Landforms, 21:749-763
Date: 1996

Location: Raba River, Western Carpathians, Poland
Watershed Characteristics:
The length of the reach studied is 26.75 km. The channel slope ranges from 0.00117 to 0.00068 at the lower and upper station respectively. Mean annual discharge ranges from 12.1 m^3/s to 17.6 m^3/s. The basin has high relief and low forest cover.
Management:
The Raba River was first channelized in the early 1900s and continued in the late 1950s.

Objective and Methodology:

The purpose of this study was to determine changes in flood flows in the Raba since its channelization. Data were collected at two gages upstream and downstream of the channelized reach. These gages were used to measure temporal changes in spatial transformation of flood waves. Historical records of daily and maximum annual discharges were available since 1951 and 1921 respectively. The effects of channel changes on flood waves were determined from a ratio of annual peak discharge downstream gage to annual peak discharge at the upstream gage.

Results and Discussion:

Two stages in the geomorphic evolution of the stream occurred in the time period studied. Initially, the vertical channel position was stable and sinuosity increased from the 1920s to the 1940s. This change allowed the system to attenuate flood waves. Thus, the inflow and outflow peak discharges were very similar. This was demonstrated by the 1940 ratio of outflow (downstream) peak discharge to inflow (upstream)peak discharge of 1.06. The similar flows were attributed to increased floodplain storage. However, in 1950, channelization occurred. As a result, degradation narrowed and straightened the channel. Channel incision magnified peak flows of flood waves, as shown in the 1970 outflow to inflow ratio of 2.41. The study concluded that concentration of flow in a channel zone greatly reduces floodplain storage

Streamflow hydrographs were examined for flood waves with similar inflow peaks. Floods from 1949, 1962, and 1972 produced corresponding outflow peaks of about 700 m^3/s, 875m^3/s, and 900m^3/s. These results also suggested a progressive increase in the amount of downstream peak flow magnification.

APPENDIX 3- ABSTRACTS FOR ECOLOGICAL IMPACT LITERATURE REVIEW

Micro-storms

Criteria: Important processes/mesic north/temperate watershed
Relevance: Effects of micro-storms on fish

Title: The Flood of July 25th 1983 on the Hermitage Water, Roxburghshire
Author: Acreman, M.
Source: Scottish Geographical Magazine, 107(3):17-178
Date: 1991

Location: Scotland
Land Use: agriculture/pasture
Watershed Characteristics: 39 km^2

Objective and Methodology:

Report human and environmental damages incurred during an intense (65 mm in 75 minutes) thunderstorm flood (170 m^3/sec) in a small Scottish catchment.

Results and Discussion:

Found that hillslope failure and riverbank erosion introduced massive quantities of sediment into the stream, resulting in major fish kills.

Urbanization, Agriculture, Logging
Criteria: mesic north temperate watersheds/important processes/important research approaches
Relevance: Effects of land use on water quality and biotic community integrity

Title: Influence of Catchment Land Use on Stream Integrity at Multiple Spatial Scales
Author: Allan, J.D., D. Erickson, and J. Fay
Source: Freshwater Biology, 37:149-161
Date: 1997

Location: southeastern Michigan - River Raisin drainage
Land Use: forest/agriculture/urban
Watershed Characteristics: mesic north-temperate watersheds underlain by glacial till and outwash in the upper part of the basin, lake deposits in the lower part of the basin.

Objective and Methodology:

Using GIS, combined with water quality and biological monitoring (fish sampling) in tributaries of the River Raisin, assessed the relationship between land use and stream ecosystem integrity at two spatial scales: the proportion of the watershed in agricultural use (large scale), and the amount of riparian cover within a local stream site (small scale). Stream integrity was measured using estimates and model predictions of suspended sediment yield, habitat heterogeneity, and biotic integrity of fish communities, with some information on nitrogen and phosphorus yield.

Results and Discussion:

Sediment yields were strongly correlated with the proportion of the watershed in agricultural use during both low-flow and storm-flow periods. Both a habitat quality index, and a fish community biotic integrity index were negatively correlated with agricultural use. Small-scale land use (riparian cover) had a minor effect, compared to large-scale land use, on stream integrity. Model predictions indicated that runoff, suspended sediment, nitrogen, and phosphorus increased significantly with both increasing agriculture and increasing urbanization, and conversely, that reforestation can significantly reduce sediment and nutrient loading to streams.

General Ecology, Stream Ecology, Land Use

Criteria: Important Concept

Title: Stream Ecology: Structure and Function of Running Waters
Author: Allan, J.D.
Source: Chapman & Hall, London
Date: 1995

Summary:

Most up-to-date general treatment of both basic and applied issues in stream ecology. Essentially replaces Hynes (1970) "The Ecology of Running Waters". All chapters are straightforwardly written, making this text useful to the interested layperson. Sections on the links between geomorphology, hydrology, and ecology, and on land use effects in stream ecosystems, are particularly valuable for applied issues.

Agriculture, Logging
Criteria: Important process/ temperate mesic watersheds
Relevance: Effects of land use on aquatic invertebrates

Title: Differential Response of Benthos to Natural and Anthropogenic Disturbances in 3 Lowland Streams
Author: Armitage, P.D. and R.J.M. Gunn
Source: Internationale Revue Der Gesamten Hydrobiologie, 81(2):161-181
Date: 1996

Location: southeast England
Watershed Characteristics: small lowland watersheds

Objective and Methodology:

The macroinvertebrate faunal assemblages of 8 sites on three small streams in SE England were examined annually in spring between 1987 and 1993. Considerable 'natural' variability was observed in the sites superimposed over a background of low-intensity anthropogenic disturbance such as farming, quarrying, and urban influences. Landscape changes and activities in the catchment (saline drainage, removal of topsoil, pipeline crossings of streams) associated with the construction of the UK terminal for the Channel Tunnel, resulted in further temporary disturbance at some of the sites.

Results and Discussion:

Most changes in faunal composition were related to natural and anthropogenically induced modifications of the stream substrate. The response and recovery time of sires to disturbances was very variable and was related to the hydraulic and substrate characteristics of the stream bed, with least change and quickest recovery at sites with coal substrates and high slope. Variations between years in the occurrence of taxa were generally more apparent with species data than with family data except where environmental change was great. Despite the observed differences in faunal composition the main elements of the fauna were fairly constant throughout the study period.

Agriculture, Logging

Criteria: mesic, originally forested watersheds/northeast region
Relevance: effects of agricultural land use on stream invertebrate communities

Title: The Use of Percent Model Affinity to Assess the Effects of Agriculture on Benthic Invertebrate Communities Headwater Streams of Southern Ontario, Canada
Author: Barton, D.R.
Source: Freshwater Biology, 36(2):397-410
Date: 1996

Location: southern Ontario
Land Use: forest/agriculture
Watershed Characteristics: 213 headwater streams

Objective and Methodology:

Compared invertebrate communities in agricultural vs. forested headwater streams by assessing percentage similarity of invertebrate communities.

Results and Discussion:

Found that in close to 80 % of the sites percent model affinity distinguished agricultural sites from forested, reference sites. Differences in benthic communities between agricultural and forested sites were greatest early in the growing season. Agricultural streams which were also channelized and dredged were more dissimilar to reference sites than were unchannelized agricultural streams.

Agriculture, Channelization/Dredging
Criteria: Important process/mesic temperate watershed
Relevance: Effects of dredging and construction activities on fish communities

Title: Changes in Biotic Integrity of a River in North-central Tennessee
Author: Crumby, WD, M.A. Webb, F.J. Bulow, and H.J. Cathey
Source: Transactions of the American Fisheries Society, 119(5):885-893
Date: 1990

Location: Roaring River, Tennessee, southern Appalachian region
Land Use: forest
Watershed Characteristics: small, high-gradient watershed
Management: stocking of non-native fishes

Objective and Methodology:

Fish species composition and index of biotic integrity of Roaring River, Tennessee, were assessed, via electrofishing in 1972 and 1986. During the intervening years, a fish barrier dam was constructed in the river, heavy gravel dredging occurred, and the watershed was disturbed by bridge construction, highway construction, and poor agricultural practices. In addition, exotic species were introduced to the watershed.

Results and Discussion:

Native fish species and overall biotic index values, and game species declined over the course of the 14-year period, while exotic and environmentally-tolerant species increased. The authors attributed this change largely to effects of river disturbance from dredging and agricultural practices which resulted in an increase in sediment lading to the river. However, effects of exotic species could not be ruled out as a causal factor.

Micro-storms

Criteria: Important process/mesic temperate mesic watersheds
Relevance: Effects of micro-storms on fish communities

Title: Effects of Winter Floods on Threespine Sticklebacks in a Restored Urban Creek
Author: Gillooly, J.
Source: California Fish And Game, 81(4):155-162
Date: 1995

Location: Bay Area California
Land Use: urban/suburban
Watershed Characteristics: small coastal watershed

Objective and Methodology:

Used electrofishing surveys to assess the effects of winter floods on a restored fish population in an urban stream.

Results and Discussion:

Winter floods reduced stickleback populations in both 1992 and 1993. In both years, however, populations rebounded in the spring. The author attributes population resilience to individuals finding refuge and recolonizing following storm events.

Urbanization, Agriculture, Logging

Criteria: mesic north temperate watersheds/important processes/important research approaches
Relevance: Effects of land use on fish communities

Title: The Effects of Land-use Characteristics and Acid Sensitivity on the Ecological Status of Maryland Coastal Plain Streams
Author: Hall, L.W., M.C. Scott, W.D. Killem, and R.D. Anderson
Source: Environmental Toxicology And Chemistry, 15(3):384-394
Date: 1996

Location: Maryland coastal plain/piedmont
Land Use: forest/agriculture/urban

Objective and Methodology:

Correlated land-use activities (forested streams vs. agricultural dominated streams) and watershed size in 24 coastal plain streams with biological, chemical, and physical conditions. These data were also used to determine if a poor IBI for coastal plain stream fish can be related to stream sensitivity from acidic inputs.

Results and Discussion:

Found that biotic integrity of fish communities was more closely related to physical habitat than water quality characteristics. Agricultural sites had higher niotic integrity than forested streams. The authors suggest that this is a result of forest cover being positively associated with urbanization, which has a negative effect on community integrity

Logging
Criteria: mesic north temperate watersheds/important processes/important research approaches
Relevance: Effects of logging on a game fish population

Title: Impacts of Logging in Carnation Creek, a High-energy Coastal Stream in British Columbia, and Their Implication for Restoring Fish Habitat
Author: Hartman, G.F., J.C. Scrivener, and M.J. Miles
Source: Canadian Journal of Fisheries and Aquatic Sciences, 53(SUPPL. 1):237-251
Date: 1996

Location: Carnation Creek, coastal British Columbia
Land Use: forest/logged
Watershed Characteristics: small, steep slopes
Management: instream habitat manipulation

Objective and Methodology:

Use long-term (> 20 year) data set on changes in physical habitat, water chemistry, hydrology, and coho salmon production to assess the affects of clearcut logging.

Results and Discussion:

Found that massive hillslope failure and runoff erosion during winter storms resulted in major inputs of sediment to the stream channel. These inputs degraded spawning and rearing habitat, destroyed habitat improvement structures, and resulted in the decline of coho salmon populations.

Micro-storms

Criteria: Important process/mesic temperate mesic watersheds
Relevance: Effects of micro-storms on aquatic invertebrates

Title: Impact of Flooding on the Densities of Selected Aquatic Insects
Author: Hendricks, A.C., L.D. Willis, and C. Snyder
Source: Hydrobiologia, 299(3):241-247
Date: 1995

Location: South River, Virginia
Watershed Characteristics: small Piedmont watershed

Objective and Methodology:

Data from a four-year study of five aquatic insect species, Hydropsyche betteni, H. morosa, H. bronta, Isonychia bicolor, and Ephoron leucon, were utilized to evaluate the impact of a 60-year flood and a few lesser floods. The survey began in August, 1984 and was terminated in October, 1987 with the 60-year flood occurring in November, 1985. Four sampling sites were established on the South River and six quantitative samples were taken each month from each site. Gauging stations on the South River provided accurate discharge data for the sampling sites and useful historical data. Densities for the five species were utilized in the evaluation of the floods.

Results and Discussion:

Densities were reduced to less than 50% of their average values immediately after the 60-year flood for the three Hydropsyche spp. and at three sites for I. bicolor. Ephoron leucon showed no response to the 60-year flood. Densities of the four impacted species returned to previous levels in the following generation. The 60-year flood was considered a disturbance in the near term but not for more than one generation.

Urbanization, Agriculture, Logging
Criteria: mesic, originally forested watersheds
Relevance: Effects of land use on nutrient concentrations

Title: The Determination of Total Nitrogen and Total Phosphorus Concentrations in Freshwaters from Land Use, Stock Headage and Population Data: Testing of a Model for Use in Conservation and Water Quality Management
Author: Johnes, P., B. Moss, and G. Phillips
Source: Freshwater Biology, 36(2):451-474
Date: 1996

Location: England
Land Use: forest/agriculture/suburban
Watershed Characteristics: ten watersheds, moderate to low gradient hillslopes, watershed areas of 4900 - 18,000 ha.

Objective and Methodology:

Developed and tested an export coefficient model for nitrogen and phosphorus, then applied the model to assess the effects of temporal trends in land use change on nitrogen and phosphorus in stream water.

Results and Discussion:

Found that a reduction in low-intensity land use ("rough" grazing), and an increase in high-intensity land-use (intensive agriculture and grazing) over a 40-40 year period more than doubled the flows of nitrogen and phosphorus. In these catchments, waste from grazing stock have been the greater contributors to N and P exports, while increases in cultivation have had the second strongest effect on nitrogen, and increased human population had the second strongest effect on phosphorus.

Urbanization, Agriculture, Logging
Criteria: mesic north temperate watersheds/important processes/important research approaches
Relevance: Effects of land use on water quality

Title: Landscape Influences on Water Chemistry in Midwestern Stream Ecosystems
Author: Johnson, L.B., C. Richards, G.E. Host, and J.W. Arthur
Source: Freshwater Biology, 37:193-208
Date: 1997

Location: central Michigan -Saginaw Bay catchment
Land Use: forest/agriculture/urban
Watershed Characteristics: mesic north-temperate watersheds underlain by glacial till and outwash, or lake deposits

Objective and Methodology:

Using GIS mapping of 62 subcatchments, combined with water quality monitoring (fish sampling), assessed the relationship between land use (proportion of catchment or ecotone in agriculture, catchment geology, and landscape structure (gradient, patch structure) and stream water quality, focusing on water chemistry. Parameters measured included total nitrogen, nitrite + nitrate, dissolved solids, suspended solids, and alkalinity.

Results and Discussion:

Catchments dominated by agriculture had the highest alkalinity, dissolved and suspended solids, and highest nitrite + nitrate. Catchment geology and landscape structure, and interactions between all three categories, had significant impacts on water chemistry; these influences also varied seasonally.

Channelization/Dredging

Criteria: New England Rivers
Relevance: Effects of river dredging and pollution on game fish populations

Title: Life History, Latitudinal Patterns, and Status of the Shortnose Sturgeon, Acipenser Brevirostrum
Author: Kynard, B.
Source: So Environmental Biology of Fishes, 48:319-334
Date: 1997

Location: New England
Land Use: forest/agriculture suburban/urban
Watershed Characteristics: large mesic watersheds

Objective and Methodology:

Using long term population data, assessed trend in the population status of the shortnose sturgeon, a critically endangered anadromous fish native to Atlantic coast drainages

Results and Discussion:

Long-term decline of the species, particularly over its southern range in New England, is attributed to river management practices in the lower reaches of major river systems, particularly impoundment and dredging for navigation, along with urban and industrial pollution.

General Ecology, Stream Ecology, Lake Ecology, Land Use
Criteria: Important Concept

Title: Limnoecology: the Ecology of Lakes and Streams
Author: Lampert, W. and U. Summer
Source: Oxford University Press, New York
Date: 1997

Summary:

Recent volume which attempts to unify some of the often disparate literature, theory and concepts in lake and stream ecology. The text is difficult for the lay person to follow, and in some ways poorly organized. However, the book is quite up-to-date, and the extensive treatment of the European literature, and ability to deal with lake and stream issues in a single volume, are advantages.

Urbanization, Agriculture, Logging
Criteria: Important processes/mesic temperate watershed
Relevance: Effects of land use on water quality and aquatic biota

Title: Effects of Land-use on Water Quality and Aquatic Biota of 3 North Carolina Piedmont Streams
Author: Lenat, D.R. and J.K. Crawford
Source: Hydrobiologia, 294(3):188-195
Date: 1994

Location: North Carolina, Piedmont region
Land Use: forest/agriculture/urban
Watershed Characteristics: small watersheds in hilly, piedmont terrain

Objective and Methodology:

Using GIS, water quality, and biological sampling, measured the effect of land use (forested, agricultural, urban) on water quality and biota along multiple sampling stations in three piedmont stream systems. Measured the concentrations of pesticides and PCB's in fish tissue and stream sediment in watersheds dominated by forest, dryland farming, irrigated farming, and urban land use.

Results and Discussion:

Suspended-sediment yield was greatest for the urban catchment and least at the forested catchment. Suspended-sediment concentrations during storm events followed this same pattern, but at low-moderate flows suspended-sediment concentrations were greatest at the agricultural site. Most nutrient concentrations were highest at the agricultural site, and the amount of 'available' dissolved nitrogen was elevated at both the urban and agricultural sites. High concentrations of metals (totals) in the water column were sometimes observed at all sites, but maximum average concentrations were recorded at the urban site (especially Cr, Cu, and Pb). Maximum sediment metal concentrations, however, were not found at the urban site, but were usually recorded at the forested site. Only minor differences were noted between fish communities of the forested and agricultural sites, although both abundance and average size of some species increased at the agricultural site. The fish community at the urban site was characterized by low species richness, low biomass, and the absence of intolerant species.

Invertebrate taxa richness, a biotic index, and the number of unique invertebrate species (found at only one site) indicated moderate stress (Fair water quality) at the agricultural site and severe stress (Poor water quality) at the urban site. At the agricultural site, declines in taxa richness within intolerant groups were partially offset by increases within tolerant groups. The agricultural stream had the highest abundance values, indicating enrichment. The urban site, however, was characterized by low species richness for most groups and very low abundance values. Dominant macroinvertebrate groups shifted from Ephemeroptera at the forested site, to chironomidae at the agricultural site, and Oligochaeta at the urban site. There was little between-site overlap in dominant species (8-17%), indicating that land use strongly influenced the invertebrate community. Chemical and physical parameters measured at the three sites did not seem sufficient to account for all of the observed differences in the invertebrate communities, suggesting some unmeasured toxicity. Biological measurements, especially macroinvertebrates community structure, consistently indicated strong between-site differences in water and habitat quality.

Micro-storms
Criteria: Important process/mesic temperate watersheds
Relevance: Effects of micro-storms on fish communities

Title: Response of a Stream Fish Assemblage to a Severe Spate in Northern Spain.
Author: Lobon Cervia, J.
Source: Transactions of the American Fisheries Society, 125(6):913-919.
Date: 1996

Location: northern Spain
Land Use: forest/agriculture
Watershed Characteristics: small high-gradient watershed

Objective and Methodology:

Sampled fish communities at nine sites along three streams in the Esva River basin before and after a major spate. In addition, brown trout and Atlantic salmon that had been marked in two streams prior to the spate permitted a direct evaluation of the immediate effects. Because the spate occurred at the spawning time and destroyed reproductive habitats, the effects upon the recruitment of that year-class of brown trout was also examined.

Results and Discussion:

There was no evidence of negative effects of the spate upon any of the variables examined. The persistence of the site-specific populations after the spate was independent of site characteristics and the corresponding numbers and sizes of fish. The recruitment of brown trout was successful and similar to that of previous years. The author suggested that mechanical responses related to microhabitat use permit brown trout and Atlantic salmon to withstand spates.

Agriculture, Logging

Criteria: mesic, originally forested watersheds
Relevance: Effects of land use on fish communities

Title: Development and Validation of an Index of Biotic Integrity for Coldwater Streams in Wisconsin
Author: Lyons, J., L. Wang, and T.D. Simonson
Source: North American Journal of Fisheries Management, 16(2):241-256
Date: 1996

Location: Wisconsin
Land Use: forest/agriculture

Objective and Methodology:

Using stream surveys, develop metrics for fish communities of coldwater ($<$ 22 degrees C maximum summer water temperatures) streams to serve as bioindicators of environmental degradation.

Results and Discussion:

Fish community metrics which correlated with environmental disturbance for coldwater streams included proportion of tolerant species, and proportion of total fish which were brook trout. In marked contrast to warmwater streams, where species richness decreases with increased degradation, species richness was lowest in high-quality coldwater streams. This result underscores the problem of applying biological criteria for warmwater streams to coldwater streams.

Stream Ecology, Logging/Forest/Rangeland Practices

Criteria: Important Concept

Title: Influences of forest and rangeland management on salmonid fishes and their habitats
Author: Meehan, W.R. editor
Source: American Fisheries Society Special Publication 19, Bethesda, Maryland
Date: 1991

Summary:

Intensive treatment and extensive review of all aspects of forest and rangeland management practices on economically and ecologically important salmonid fishes. Although the perspective and literature is somewhat biased towards Pacific Northwest issues, does address northeastern issues and species. Excellent illustration of the way in which a single practice (logging) can have a wide range of important effects. Includes a good introductory chapter on stream ecosystems, along with useful chapters on economic, regulatory, and technical considerations.

Urbanization, Agriculture, Logging
Criteria: Important processes/mesic north/temperate watershed
Relevance: Effects of land use on toxic chemical concentration of stream water

Title: The Relationship Between Land Use and Organochlorine Compounds in Streambed Sediment and Fish in the Central Columbia Plateau, Washington and Idaho, USA
Author: Munn, M.D. and S.J. Gruber
Source: Environmental Toxicology and Chemistry, 16(9):1877-1887
Date: 1991

Location: Pacific Northwest
Land Use: forest/agriculture/urban

Objective and Methodology:

Measured the concentrations of pesticides and PCB's in fish tissue and stream sediment in watersheds dominated by forest, dryland farming, irrigated farming, and urban land use.

Results and Discussion:

Found that fish tissue and stream sediments were free of organochlorine compounds only in watersheds dominated by forest. Only hexachlorobenzene was significantly different between the three other land use types, being greatest in watersheds dominated by dryland farming. In agricultural areas irrigated by surface water, Sigma DDT concentrations in both streambed sediment and fish tissue were related to the percentage of land irrigated by water delivered via furrows (gravity irrigation), although Sigma DDT was not detectable in bed sediments until gravity irrigation exceeded 30%. The relation between gravity irrigation and soil erosion supports the importance of controlling soil erosion in order to reduce the overall loading of organochlorine compounds to surface waters.

Stream and Lake Ecology, Land Use
Criteria: Important Concept

Title: Restoration of Aquatic Ecosystems
Author: National Research Council (J Cairns, Jr, Chairman)
Source: National Academy Press Washington, DC
Date: 1992

Summary:

Extensive overview of aquatic ecosystem restoration theory and practice. Includes general review of ecosystem restoration of rivers, lakes, and wetlands, along with sections on regulatory policy, nationwide assessment of water resources and detailed case studies. By focusing on change to ecosystem processes and the approaches used to deal with them, provides an excellent illustration of the way in which ecosystems work, and the way in which various interest groups deal with aquatic ecosystem issues.

Agriculture, Logging
Criteria: Important process/mesic temperate watersheds
Relevance: Effects of land use and riparian condition on aquatic invertebrate communities

Title: The Influence of Riparian Management on the Habitat Structure and Macroinvertebrate Communities of Upland Streams Draining Plantation Forests
Author: Ormerod, S.J., S.D. Rundle, E.C. Lloyd, and A.A. Douglas
Source: Journal of Applied Ecology, 30(1):13-24
Date: 1993

Location: Wales
Land Use: forest/moorland
Watershed Characteristics: small, low-medium gradient watersheds
Management: riparian restoration

Objective and Methodology:

Aquatic invertebrate communities were sampled in 66 small upland catchments under a number of different land-use scenarios, with the objective of assessing the effects of re-establishment of natural riparian vegetation on aquatic invertebrate taxon richness during commercial forestry.

Results and Discussion:

Invertebrate taxon richness was negatively correlated with the percentage of land use as pine plantation, due to lower pH associated with effects of planting pine on land which had previously been moorland. However, catchments dominated by pine plantations with riparian buffer strips of moorland had higher taxon richness than streams without buffer strips, suggesting that riparian restoration may help to ameliorate watershed-scale land-use change.

Agriculture, Channelization/Dredging, Micro-storms
Criteria: Important processes/important research approaches
Relevance: Effects of micro-storms and land use on fish communities

Title: Influence of Habitat Complexity on Resistance to Flooding and Resilience of Stream Fish Assemblages
Author: Pearsons, T.N., H.W. Li, and G. Lamberti
Source: Transactions of the American Fisheries Society, 121:427-436
Date: 1992

Location: north-central Oregon
Land Use: agriculture/rangeland
Watershed Characteristics: 21,000 ha, grassland

Objective and Methodology:

Censussed fish populations before and after intense, localized stormflood events in high habitat complexity vs. low habitat complexity stream sites. Used these censuses to assess fish community resistance (change in species abundance immediately following disturbance) and community resilience (time before pre-disturbance stream community structure was re-established, and determine habitat complexity affected resistance and resilience.

Results and Discussion:

Found that fish communities were relatively resilient, re-establishing pre-disturbance structure following major flood disturbance. Complex reaches were more resistant and resilient than simple reaches. The authors suggest that habitat complexity, by providing refuge from disturbance, helps fish communities rapidly recover from intense local flooding, and that land practices such as agriculture and grazing which reduce habitat complexity, may hinder recovery.

Urbanization, Agriculture, Logging
Criteria: mesic north temperate watersheds/important processes/important research approaches
Relevance: Effects of land use on invertebrate communities

Title: Catchment and Reach-scale Properties as Indicators of Macroinvertebrate Species Traits
Author: Richards, C., R.J. Haro, L.B. Johnson, and G.E. Host
Source: Freshwater Biology, 37:193-208
Date: 1997

Location: central Michigan -Saginaw Bay catchment
Land Use: forest/agriculture/urban
Watershed Characteristics: mesic north-temperate watersheds underlain by glacial till and outwash, or lake deposits

Objective and Methodology:

Using GIS mapping of 58 subcatchments, combined with aquatic invertebrate sampling, assessed the effect of catchment-scale land use, catchment geology, and landscape structure and reach-scale physical factors on invertebrate species and community characteristics.

Results and Discussion:

Invertebrate species traits were more strongly associated with reach-scale habitat attributes than with catchment characteristics. At the catchment scale, because land use (proportion of land in agriculture) was strongly correlated with catchment geology, it was not possible to independently assess land use affects on invertebrates.

Urbanization, Agriculture, Logging
Criteria: mesic, originally forested watersheds
Relevance: Effects of land use on fish communities

Title: Fish Assemblages as Indicators of Environmental Degradation in Maryland Coastal Plain Streams
Author: Scott, M.C. and L.W. Hall
Source: Transactions of the American Fisheries Society, 126(3):349-360
Date: 1997

Location: Maryland, coastal plain/piedmont
Land Use: forested, agriculture, suburban, urban
Watershed Characteristics: medium to gentle gradients

Objective and Methodology:

Using surveys of physical and chemical characteristics, along with electrofishing surveys of fish communities, assessed the correlation between watershed disturbance and fish community characteristics via multivariate gradient analysis. Overall study goal was to develop fish community metrics to serve as bioindicators of environmental degradation.

Results and Discussion:

Multivariate analyses identified a major gradient in watershed disturbance, both agriculture, and urban, which involved increasing fine sediment and nutrient loading, and reduced habitat diversity. Reduced species richness, reduced abundance of tolerant species, and reduced abundance of game fishes which depended on clean substrates for spawning was significantly associated with this disturbance gradient.

Agriculture
Criteria: Important review, important process
Relevance: Effects of agricultural practices on water quality

Title: Degradation of Persistent Herbicides in Riparian Wetlands
Author: Stoeckel, D.M., E.C. Mudd, and J.A. Entry
Source: Acs Symposium Series, 664:114-132
Date: 1997

Land Use: agriculture
Management: riparian clearing vs. riparian conservation

Objective and Methodology:

Determine whether the presence of seasonally flooded riparian wetlands influence the degradation and mobility of three persistent herbicides: atrazine (a triazine), fluometuron (a substituted urea), and trifluralin (a dinitroaniline).

Results and Discussion:

Data suggest that seasonally-flooded riparian wetlands enhance immobilization and degradation of persistent herbicides. While natural riparian wetlands should not be used to treat point-source herbicide pollutants, the literature indicates that maintenance of riparian wetlands can help to slow migration of and to enhance degradation of herbicides from nonpoint sources.

Urbanization, Agriculture, Logging
Criteria: Important process, mesic watershed
Relevance: Effects of urbanization on nutrient loading to streams

Title: Patterns of Nutrient Loading in Forested and Urbanized Coastal Streams
Author: Wahl, M.H., H.N. McKellar, and T.M. Williams
Source: Journal of Experimental Marine Biology and Ecology, 213(1):111-131
Date: 1997

Location: Florida
Land Use: urban vs. forest

Objective and Methodology:

Compared runoff characteristics, carbon, and nutrient loading between an urbanized and a forested watershed.

Results and Discussion:

Found that carbon and nutrient loading was greater in the urbanized watershed. While dissolved organic carbon concentration was lower in the urbanized, increased discharge resulted in higher total carbon loading. Nitrogen concentration, particularly nitrate, was higher in the urbanized watershed leading to markedly increased nitrogen loading. Not only loading rates, but also the timing of nitrogen inputs differed between the two watersheds. Nitrogen pulses were highly seasonal in the forested watershed, but occurred throughout the year in the urbanized watershed.

Stream and Lake Ecology
Criteria: Important Concept

Title: Limnology (2nd Ed.)
Author: Wetzel, R.G.
Source: Saunders, Philadelphia
Date: 1983

Summary:

While focusing largely on lake ecosystems, this text remains a major source book on general freshwater ecology. Particularly essential are the sections on physical and chemical properties of freshwaters, nutrient cycling, energy flow, and primary production. Of limited use to the layperson, this text is a must for the professional.

APPENDIX 4- GLOSSARY

GLOSSARY

aggradation: the process where particles carried by flowing water are deposited along the bottom, sides, levees, and floodplains of a stream resulting in an upward change in the channel bed and the water level. See figure 4.

alkalinity: measure of the net effect of cations and anions in water expressed as milligrams CaCO3 per liter.

alluvial: a mass of loose unconsolidated rock material consisting of gravels and sands that is transported by the stream.

aquatic: fresh water rivers, streams, brooks, lakes, ponds (pertaining to environments dominated by water including lakes, streams, rivers and oceans-include a separate entry for freshwater: body of water with a Concentration of sodium chloride (salt) appreciably less than that of sea water example lakes, rivers).

bankfull: the elevation of the water surface in a stream flowing at channel capacity before it overtops its banks and begins to flood.

baseflow/low flow: dry weather stream flow conditions.

basin: a physiographic feature capable of collecting, storing and discharging water through a stream or system of streams.

bed: bottom of stream. See figure 4.

bedload: large or coarse materials moving along the bed of a channel. Bedload is a function of the speed and volume of flow.

bioindicator: a biological attribute which is affected by an environmental change, and therefore serves to indicate when a change has occurred.

biotic integrity: the degree to which an environment maintains the biological attributes characteristic of an undisturbed system.

BOD: biochemical oxygen demand is the amount of oxygen consumed by microorganisms while stabilizing or degrading carbonaceous and nitrogenous compounds.

channel: the depression in a valley where a natural body of surface water flows or may flow. See figure 4.

channel capacity: maximum amount of water that can flow in a stream.

channel incision: the downward erosion of the stream bed.

channelization: removal of obstructions by straightening, deepening or lining with concrete.

conservation practices: practices designed to minimize the effects of change on physical, chemical and biological attributes of the environment (general definition) erosional forces and loading of sediments to waterways.

cross-sectional area: the area of a plane that transects a stream perpendicular to its long axis.

debris flows: a mass movement of coarse grained materials during high stream flow usually resulting from heavy rain events.

delivery rate: the magnitude of sediment or other material delivered to the stream over some period of time.

detritus: undissolved organic or inorganic material resulting from the decomposition of parent material.

dissolved oxygen: the dissolved oxygen content is a measure of the ability of surface waters to support aquatic life. Oxygen, which is dissolved in water, is available to aquatic animals for respiration.

dredging: excavating earth material at the bottom of a stream, or from saturated soils adjacent to the stream channel.

ecosystem: all living organisms and their environment in a defined area such as a watershed.

flood magnitude: the absolute size of the peak discharge of a given flood event.

flood frequency: the probability of how often a flood of a given size occurs in a particular stream or watershed.

floodplain: area of land adjacent to a stream which is periodically covered by water when a stream overflows its banks. See figure 4.

flow/discharge: the movement of water. Discharge is the rate of flow at past a given point at a given moment in time. Expressed as volume per unit of time.

geomorphic: the cycle of erosion and sedimentation where natural forces wear away the uplands and deposit materials in the lowlands.

glide: slowly-flowing, relatively shallow stream section with little or no surface turbulence.

habitat: the physical and biological environment experienced by an organism

habitat unit: a discrete section of space of a particular habitat type, bounded by habitats of other types

hardness: the amount of calcium and magnesium ions present in water. Increasing Ca and Mg increases hardness. Expressed in parts per million CaCO3.

Holocene: an epoch of the quaternary period, from the end of the Pleistocene to the present time. Ten-thousand years ago to present.

hydro-geomorphic: the combination of hydrologic and geomorphic processes acting on a stream channel or in a watershed.

hydrologic: description of the continuous movement of water as it passes in and out of the various storage areas on earth and in the atmosphere.

invertebrates: animals that lack a backbone such as mollusks and arthropods.

lag time: elapsed time from one event to another.

meandering: a stream where water moves through curves or bends.

microbes: organisms too small to be seen with the unaided eye; generally members of the kingdoms Monera (bacteria and blue-green algae) and Protista (Protozoans).

micro-storm: a sudden, intense precipitation event limited in both extent and duration.

nutrients: chemical compounds (such as nitrogen, phosphorus, potassium, calcium, magnesium and sulfur) required by organisms for physiological processes.

organic: including or pertaining to living things (organisms).

overbank: not contained within the stream channel.

peak flow/discharge: the highest discharge to occur during a single flood event.

photosynthesis: the chemical process by which organisms (generally plants) containing chlorophyll convert the energy contained in solar radiation and carbon dioxide into carbohydrates for metabolism and growth.

perennial: (stream) a stream in whose channel water is always present.

piscivores: fish which eat other fish.

pools: portion of a stream with reduced current velocity, usually with deeper water than surrounding areas, and a smooth surface (compare glide, riffle).

reach: a straight, continuous, or extended part of a stream, viewed without interruption as between two bends or chosen between two points.

riffles: shallow section of a stream with rapid current and a surface broken by gravel, rubble, or boulders (compare glide, pool).

riparian zone: the transition zone between the flowing water of the stream and terrestrial ecosystems (streamside, vegetation buffer zone). See figure 4.

runoff: water that cannot be absorbed into the ground.

sedimentation: the process of accumulating sediment in layers.

sediment transport: the movement and carrying away of sediment.

sediment discharge/loads/yields: the amount of sediment moved by a stream in a given time measured by dry weight or volume.

shear stress: that component of stress which acts tangential to a plane through any given point on a body.

sinuosity: ratio of the length of the channel to the down-valley distance.

snowmelt: water resulting from the melting of snow.

streambank: land next to the stream bed extending from the bed to the top of the natural ridge called a levee.

streambed: channel containing the water of a stream.

stream channel: the hollow bed where a natural stream of water runs or may run.

streamflow: water conveyed by a stream channel.

streamflow/channel velocity: a measure of the speed of the flowing water in a channel.

surface runoff- water which flows overland directly to the stream channel without first being stored in groundwater or other storage zone.

suspended sediment: that part of a stream's total sediment load carried in the water column (as opposed to bedload or deposited sediment).

terrestrial: pertaining to dry land (as opposed to aquatic).

tributary: stream that flows into larger bodies of water.

trophic: of or pertaining to nutrition. A trophic level is a stage of nourishment representing one of the segments of the food chain.

unit hydrograph: the relationship between the discharge in a stream per unit time relative to a given amount of rain.

watershed: entire physical area or basin drained by a distinct stream or riverine system physically separated from other watersheds by ridge top boundaries.

width to depth ratio: measurement of stream dimensions at a specific location that expresses the shape of the channel.

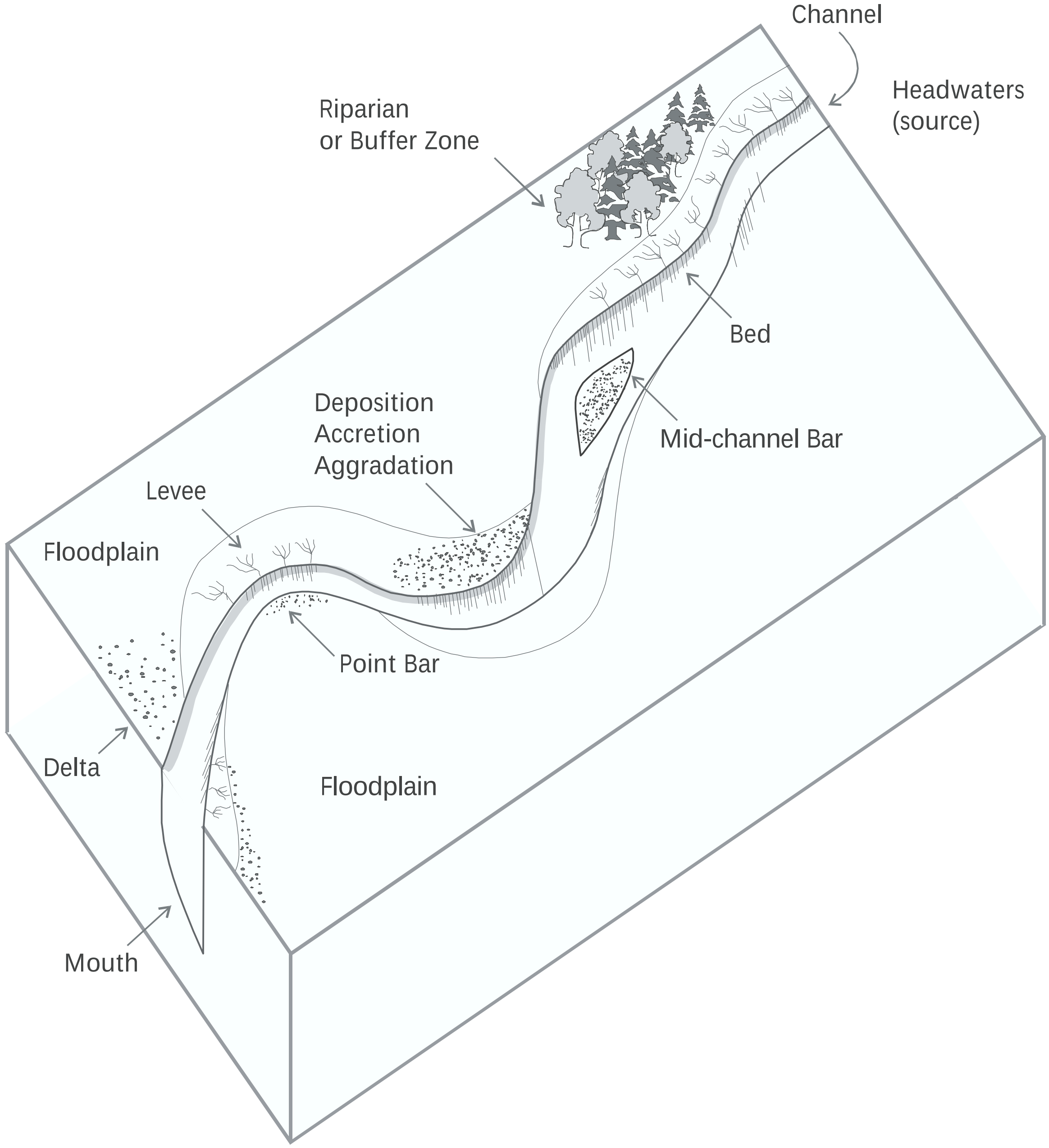

FIGURE 4: CROSS-SECTIONAL VIEW OF STREAM FORMATIONS
Watershed Hydrology Protection amd Flood Mitigation
Vermont Agency of Natural Resources, Waterbury, Vermont

Source: Modified from J.R.L. Allen, 1970
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